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THE RELATION BETWEEN AREA OF STIMULATION AND INTENSITY OF LIGHT AT VARIOUS LEVELS OF VISUAL EXCITATION AS MEASURED BY PUPIL CONSTRICTION *

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A fundamental problem in the study of the visual process is the relation between the area of the stimulus and the intensity required for a threshold response to light. Reviews of research already completed on the area-intensity problem make it clear that while a great deal of investigation has been undertaken much remains to be accomplished in the direction of a completely adequate formulation describing retinal excitation in the human eye.

Recently the area-intensity problem has been re-examined in terms of three divergent views of the visual mechanism. Each hypothesis provides a rational account of the area-intensity relationship. According to one, the retina is a mosaic of independently operating, sensitive elements whose thresholds vary with intensity in a similar fashion from one restricted region to another within the area stimulated (Wald, **13**). A constant number of elements, regardless of area, must be stimulated for a threshold response so that as the area stimulated increases additional elements are brought into play and the threshold intensity decreases. According to a second view the retina involves not only overlapping groups of rod or cone populations, in any one of which the sense organs are distributed in their threshold intensities along an intensity continuum, but also a system of converging and laterally conducting neural elements [Graham, Brown and Mote (**6**)]. The threshold is determined by neurons

* This investigation was conducted under the direction of Dr. R. H. Brown, Department of Psychology, Clark University.

centrally placed and excited by summating, but otherwise subliminal, excitation from the outlying regions of the area stimulated. As the area increases the intensity threshold decreases in accordance with a gradient of excitation, that is, the central portion of the excited area contributes most to the excitation effect and the marginal portions of the stimulated area contribute to the excitation effect in proportion to their distance from the center. Crozier (**2, 3**) rejects any attempt to account for threshold data in terms of events occurring in the retina and maintains that functional properties of the central nervous system provide a more comprehensive basis for interpretation. He assumes that the number of central nervous units or elements of excitation increases with increase of area. Excitation required for threshold effects involves two factors, first, the number of neurons affected and second, the frequency of impulses in each. When the number of active central elements is increased by increasing the size of the stimulus area a smaller density of impulses per unit area is required to produce the frequency of impulses necessary for sensorial discrimination.

Measurements of the area-intensity relation have been made by early workers and, more recently, by Wald (**13**), Crozier and Holway (**3**), and Graham and co-workers (**4, 5, 6**), in terms of absolute and differential intensity thresholds. Where conflicting hypotheses of the visual mechanism are available, it is pertinent to obtain data in terms of some index of visual excitation other than these generally used. It is with this in mind that the present investigation is undertaken.

On the basis of previous research [Brown and Page (**1**)] it seems worth while to study the problem of area and intensity in terms of pupil constriction as a measure of the extent of visual excitation. The formulations postulated by Wald and by Graham use the threshold response as a measure of visual excitation. The threshold is regarded as a constant effect. If one uses pupillary constriction as a measure of the excitation, then, in addition to having a different index of visual excitation, one may also use various constant levels of response. Thus the maximal pupillary constriction may be regarded as one constant level of response, minimal constriction as another level, and intermediate levels may also be used to test the hypotheses.

In addition, the assumption made by Wald and also by Graham that the threshold response is a constant effect has been criticized [Crozier (**2**), Crozier and Holway (**3**)]. Regardless of the validity of the criticism of the threshold as representing a constant effect, it cannot apply to measurements made in the present investigation. The use of a constant level of response involves the arbitrary selection

of a given pupil area. The intensity of the flash of light required to produce this pupil area is then determined for different sized stimulus patches. The constant level of response is thus an entity capable of definition in quantitative terms and involves no assumption of constant quantity of nerve fibres or constant number of impulses.

Since we shall wish to compare our findings with those obtained by Graham, Brown and Mote (**6**), and to fit their formulation to our data, the present experiment is patterned after their investigation. Adapting conditions for each experimental session are similar to those used in their experiment, as are the stimulus areas. Because the intensity of illumination required to produce moderate or maximal pupillary constriction is greater than that required for threshold excitation the intensities of stimulating light are greater in the present investigation. Where pupil constriction is used as a measure of excitation it is essential to use intensities of stimulating light which insure rather wide variations in pupil size. While the intensities used are not sufficient to produce complete constriction (a change in pupil diameter from approximately 9 to 2 mm for our subjects) the pupil does constrict to about 3 mm in diameter. This is more than adequate to meet our requirements.

Pupillary measurements following peripheral stimulation have been undertaken with some misgivings. On the basis of past experiments it would seem as if our method of using pupil size as a measure of visual excitation would not be applicable to peripheral determinations. Observations in earlier research indicate that variation in pupil size, with increase in intensity of illumination, is almost exclusively controlled by cones in the macular region of the retina. These observations have been reviewed in an earlier paper [Brown and Page (**1**)].

In the present investigation pupil constriction is obtained to both binocular and monocular peripheral stimulation. While the brightness of the stimulating areas used in the peripheral determinations is the same as in the foveal determinations the quantity of light entering the eye in the peripheral determinations is greater than in foveal measurements, since the areas used in peripheral measures are larger and the subject is seated nearer to the stimulus areas. When these facts are considered it is evident that the peripheral constriction is not as great as might be expected considering the intensity thresholds. The much lower intensity thresholds for the periphery of the eye would lead one to expect that a lesser intensity of stimulating light would be required to produce constriction following peripheral stimulation than would be necessary for constriction following foveal stimulation.

Apparatus and Procedure

As noted, it is desirable to compare our findings with the threshold data obtained by Graham, Brown and Mote (6). We wish to fit their formulation to our data and so have patterned the present experiment after their investigation. Adapting conditions for each experimental session are similar to those used in their experiment, as are the stimulus areas. The intensity of illumination required to produce moderate or maximal pupillary constriction is much greater than that required for threshold excitation. It is therefore necessary to use intensities of illumination much greater than are required for absolute thresholds.

In obtaining pupillary measurements following retinal stimulation by various areas and intensities of stimulating light the apparatus includes: (1) different sized stimulus areas and an optical system for illuminating them; (2) devices for controlling fixation; (3) an adaptation screen; (4) a source of infra-red rays for photographing the pupil and a timing device for controlling the exposure time; (5) a camera for photographing the pupil and microscope for measuring the size of the pupil image on the negative.

In one wall of the subject's dark room there is a metal holder in which metal slides, containing apertures, may be placed and illuminated by an optical system in an adjacent dark room. The extent of the illuminated area is regulated by circular apertures of various sizes cut in a series of metal slides. These metal slides are slid snugly into the metal holder in such a manner as to limit the light to the illumination transmitted by the circular areas. Fastened directly to the back of each of the metal plates is a paraffin-coated piece of glass. The stimulus patch appears to the subject as a circular area illuminated for 1″ with white light. The brightness of nine foveal stimulus patches, ranging in radius from 0.97′ to 30.6′ of visual angle, and of eleven peripheral stimulus patches, ranging in radius from 3.21′ to 196′ of visual angle, has been determined by means of a Schmidt and Hensch photometer and an optical bench.

The optical system for illuminating the stimulus patches is placed in a dark room adjacent to one where the subject is sitting and where the pictures are taken. Light rays from a 1000-watt Mazda lamp pass through a lens system such that at the point of convergence, where the light rays form approximately a point source, Wratten neutral tint filters may be placed for controlling the intensity of the stimulating light. As the light rays diverge they pass through the opening of a diaphragm shutter and illuminate the stimulus area placed in the wall of the subject's dark room. Direct current is used and the voltage of the lamp is kept at 120 v. by means of a rheostat in the circuit.

For peripheral determinations the subject's fixation is controlled by a foveal fixation cross located at a distance of 70 cm from the subject (as are the stimulus areas) and at a visual angle of 35° to the left of the center of the stimulus patch. Thus the position of the fixation point insures that even the largest areas fall outside the limits of the fovea and the blind-spot. The subject's head is maintained in a fixed position by means of a head rest. When the subject's head is in position the fixation cross appears as a small red cross (with arms 1 cm by 2 cm) located immediately above the camera. The brightness of the cross is maintained just above the threshold level of visibility.

Foveal fixation is provided for as follows. The subject, sitting at a distance of 230 cm from the stimulus area, with his head firmly in the head rest, regards the stimulus patch with both eyes as it appears through a circular aperture in a dimly illuminated screen placed 10 cm in front of the stimulus area. Illumination of the screen is maintained at a constant brightness of 0.02 ml throughout the experiment. Fixation under the above conditions requires that the subject regard the center of the black area in the white screen. This black area subtends a visual angle of 2° 36′. The stimulus area then appears as an illuminated patch in a black circle (6).

Adaptation conditions are important for foveal determinations. When the eye is exposed repeatedly to flashes of light of great intensity the retina fails to remain in a constant state of excitability. The pupil likewise fails to maintain a constant level of dilatation. Since it is essential that retinal excitability be constant at the time of stimulation, a light adaptation screen is provided. A period of light adaptation followed by a period of dark adaptation insures approximate constancy of excitability at the time of stimulation with different areas and intensities of stimulating light. It likewise insures in this experiment comparable pupil size at the time of stimulation, a necessity since pupil area is used as a measure of excitation. In peripheral determinations, where the subject is dark adapted for half an hour before determinations are made, light adaptation is unnecessary.

The adaptation screen used in foveal determinations consists of a box, one face of which is a plate of milked glass (25 cm by 26 cm), illuminated by four frosted glass bulbs contained within the box. The screen surface has a brightness of 335 ml and is 230 cm from the eyes of the subject. Control experiments with this adaptation screen show that pupil size before stimulation is always of the same order of magnitude.

The photographing equipment, as described in an earlier paper (1), involves essentially a source of infra-red rays and a Leica camera for photographing the pupil. The source of infra-red radiation consists of two 1000-watt Mazda lamps inclosed in an asbestos-lined, light-tight box. When a diaphragm shutter in front of the box is opened the radiation is centered on the right eye of the subject, after passing through a Wratten infra-red filter No. 87.

The infra-red radiation is exposed for 0.1″ and control experiments show that the exposure itself has no effect on the pupil size. The shutter controlling the exposure is operated mechanically by a magnet wired through a Telechron motor which makes 60 revolutions per minute. When the stimulus patch is illuminated by opening the shutter in the optical system a mercury cup attachment to the shutter closes an electrical circuit through the Telechron motor. After one revolution of the motor shaft (taking one second) the circuit through the magnet operating the shutter in front of the infra-red source is closed and the infra-red radiation strikes the eye. Since the camera shutter remains open throughout the experiment the Eastman 35 mm infra-red film is exposed when this occurs.

A Leica camera, model C, and an Elmar 50 mm lens are used to obtain the pictures. A convex, 3 diopter lens is fastened to the regular lens holder. The camera is placed 40.5 cm from the eye with the lens set at 12′ and the diaphragm at f. 4.5. At this distance the film records a relatively large image of the pupil. The camera is fitted with a trigger base plate which facilitates rapid winding of the film and is fastened in a rigid position by a steel rod screwed to the base plate of the camera and to the table.

After the completion of a series of exposures and development of the film the pupil diameter for each exposure is measured by means of a microscope with a micrometer eye-piece. Readings are accurate within 0.1 mm of pupil diameter and are not corrected for refraction by the cornea and aqueous humor. Such a correction would involve multiplying the observed diameter by a constant factor.

In foveal determinations the subject is light adapted for 15″. This is followed by 105″ of dark adaptation before any pictures are taken. Following the 2′ of combined light and dark adaptation the stimulus patch is illuminated for 1″ and a picture taken at the end of this interval. Four such pictures are taken at 7″ intervals. The same stimulus area but different intensities of illumination are used. Wratten neutral-tint filters in front of the source of light control the intensity of the illumination. The adapting conditions are then repeated and three more pictures are taken at the same intervals, thus completing a series of seven pictures following stimulation by one area illuminated by seven different intensities. This procedure is used to obtain exposures following stimulation by nine different areas. In making the determinations the order of stimulation has been from the smallest area and lowest intensity of illumination to the largest area and greatest stimulus intensity.

In all, sixty-three exposures are made in each of twenty series. Three subjects are used and in all cases pictures are taken of the right eye. The left eye remains uncovered. Aside from advancing the film in the camera and cocking the shutter in front of the infra-red source of illumination (both are accomplished by pulling a single cord) the subject takes no active part in the experiment. There are no distractions present which might influence the size of the pupil, and the subject concentrates on the fixation point for each exposure. This keeps the eye in position for photographing and aids in eliminating dilatation or constriction of the pupil to changes in accommodation. The experimenter sits in another room where he operates the shutter in front of the stimulus area and changes the stimulus areas and Wratten filters.

For peripheral determinations the subject is dark adapted for 30′. Following this period of adaptation pictures are taken at half-minute intervals. Pictures are obtained following binocular stimulation by an area illuminated in turn by light of eight different intensities. Eleven different areas are used for the peripheral determinations. Twenty series are run on each of two subjects. At the completion of a series the subject remains in the dark while the camera is reloaded. This takes approximately 5′. The procedure is then repeated with the areas presented in the reverse order. The total time required to complete the two series is two hours.

Five additional series are run with one subject. Monocular stimulation is used and the procedure is the same as that used for binocular peripheral determinations. The left eye is bandaged to prevent any light reaching the eye.

There are certain objections to the procedure we have used. We are determining the extent of pupil constriction after 1″ of stimulation. Although this time interval has been more or less arbitrarily selected the pupil has been photographed in exploratory experimentation after stimulation for 0.5″, 1.0″ and 1.5″. The constriction following 1.0″ of stimulation is greater than that following 0.5″ of stimulation. There is no difference found in the constriction following 1.0″ and 1.5″ stimulation. We are thus led to believe that the pupil reaches a maximal level of constriction in 1.0″. Reeves (10) has reported that the average pupil reaches its minimal diameter in less than 5″ after exposure to light, and the greater part of this closing occurs within 2″. It is quite possible that further experimentation with our subjects would indicate maximal constriction to a given stimulus intensity after an interval longer than 1″.

A more serious criticism can be raised concerning the duration of the stimulus flash. We use a 1″ flash throughout the investigation. It would be more advisable to use a flash of light

TABLE I

PUPIL AREAS FOR DIFFERENT AREAS OF STIMULUS IN THE FOVEA

Radius in Minutes of Visual Angle	Log Intensity in Millilamberts	JIN		IJB		ABW	
		No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)
30.6	0.59	10	46.45	10	47.80	11	48.36
	1.59	20	42.91	20	34.27	20	41.32
	2.59	20	27.98	20	25.24	20	30.12
	3.59	20	19.69	20	18.85	20	24.46
	3.99	20	16.60	20	16.23	20	21.13
	4.29	20	14.23	20	14.78	20	18.88
	4.59	21	11.98	20	12.34	20	15.81
17.9	0.40	10	46.86	10	51.98	11	55.00
	1.40	20	43.37	20	42.15	20	46.98
	2.40	20	33.97	20	30.26	20	37.12
	3.40	20	23.68	20	22.28	20	29.02
	3.80	20	19.62	20	19.25	20	25.89
	4.10	20	16.19	20	17.18	20	23.02
	4.40	20	14.53	20	15.44	20	19.76
12.7	0.58	10	47.27	10	54.29	11	56.45
	1.58	20	44.52	20	43.67	20	49.33
	2.58	20	34.79	20	31.04	20	40.56
	3.58	20	23.05	20	22.53	20	30.72
	3.98	20	20.43	20	19.61	20	27.29
	4.28	20	17.75	20	17.49	20	24.50
	4.58	20	14.52	20	14.98	20	19.98
8.21	0.73	10	47.07	10	56.06	11	56.25
	1.73	20	45.85	20	47.33	20	49.64
	2.73	20	35.73	20	33.88	20	40.62
	3.73	20	24.88	20	25.19	20	34.30
	4.13	20	21.37	20	20.15	20	29.75
	4.43	20	18.18	20	18.35	20	25.26
	4.73	20	15.90	20	15.42	20	21.44
4.86	0.55	10	48.30	10	56.51	11	57.49
	1.55	20	47.39	20	50.76	20	55.86
	2.55	20	40.71	20	41.18	20	48.02
	3.55	20	31.84	20	28.02	20	38.14
	3.95	20	25.42	20	23.43	20	33.89
	4.25	20	21.84	20	21.30	20	29.48
	4.55	20	18.78	20	17.78	20	24.97

TABLE I—*Continued*

Radius in Minutes of Visual Angle	Log Intensity in Millilamberts	JIN		IJB		ABW	
		No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)
3.00	−0.18	10	48.51	10	57.64	11	59.37
	0.82	20	47.18	20	55.84	20	59.16
	1.82	20	45.79	20	51.63	20	53.66
	2.82	20	40.42	20	40.48	20	45.82
	3.22	20	37.30	20	32.71	19	39.78
	3.52	20	35.09	20	28.31	20	35.06
	3.82	20	28.82	20	26.62	20	32.01
	4.16	20	24.41				
	4.56	20	20.59				
	4.86	20	16.97				
2.03	0.37	10	49.15	10	57.42	11	60.00
	1.37	20	47.47	20	55.50	20	59.23
	2.37	20	44.75	20	51.30	20	55.14
	3.37	20	40.55	20	41.93	20	46.23
	3.77	20	35.13	20	33.07	20	40.96
	4.07	20	32.35	20	28.99	20	36.40
	4.37	20	27.97	20	24.61	20	30.21
	4.71	20	21.74				
	5.01	20	17.86				
	5.41	20	16.13				
1.28	0.59	10	48.93	9	57.84	11	58.95
	1.59	20	47.72	19	55.36	20	58.49
	2.59	20	46.00	19	52.33	20	56.16
	3.59	20	41.81	19	44.25	20	48.32
	3.99	20	37.29	19	35.55	20	43.70
	4.29	20	33.22	19	29.56	20	36.55
	4.59	20	30.55	19	24.91	20	32.00
	4.93	20	25.02				
	5.23	20	20.99				
	5.63	20	18.05				
0.97	0.35	10	49.57	10	57.63	11	59.16
	1.35	20	47.82	20	56.29	20	59.99
	2.35	20	46.71	20	55.39	20	58.07
	3.35	20	44.58	20	49.76	20	53.01
	3.75	20	41.25	20	43.07	20	46.73
	4.05	20	38.67	20	38.81	20	42.74
	4.35	20	33.78	20	32.44	20	35.76
	4.69	20	30.01				
	4.99	20	25.26				
	5.39	20	21.89				

well within the critical duration. Graham and Margaria (7) have determined the manner in which the intensity-time relation of the peripheral retina varies as a function of the area. Karn (8) has made similar determinations for the fovea. Up to a critical duration of 0.1″ the expression $IT = C$ describes the relation for very small areas (no larger in radius than 3′ of visual angle), where I is the intensity of the stimulating light, T the time and C a constant. For large areas the critical duration, within which $IT = C$, is less than 0.1″. Beyond the critical duration there is greater dependence on intensity and the relation $IT = C$ approaches the relation $I = C$. As area decreases there is a sharper and more clear cut change from the expression $IT = C$ to $I = C$ and the absolute intensity threshold increases.

Technical difficulties prevent us from using flashes of light of very short duration. Preliminary attempts have been made to use flashes of light short enough to fall within the critical

duration of all areas. It was found impossible, however, to obtain a stimulus intensity great enough to produce marked constriction with very short flashes of light. With our largest circular area, 392′ visual angle in diameter, a flash of 0.001″ duration would be necessary to insure measurements within the critical duration where $IT = C$. For this reason it is advisable to go to the other extreme and use a flash of light of much longer duration. $I = C$ then describes the relation and time is no longer involved. With this in mind a flash of 1″ is used. On the basis of the findings of Graham and Margaria for the periphery and of Karn for the fovea we feel that we are safe in using a flash of this duration.

Results

A. Fovea

Table I presents the average results obtained from each of three subjects for foveal stimulation. From ten to twenty determinations of pupil area are available for each subject for nine different stimulus patches over a wide range of intensities.

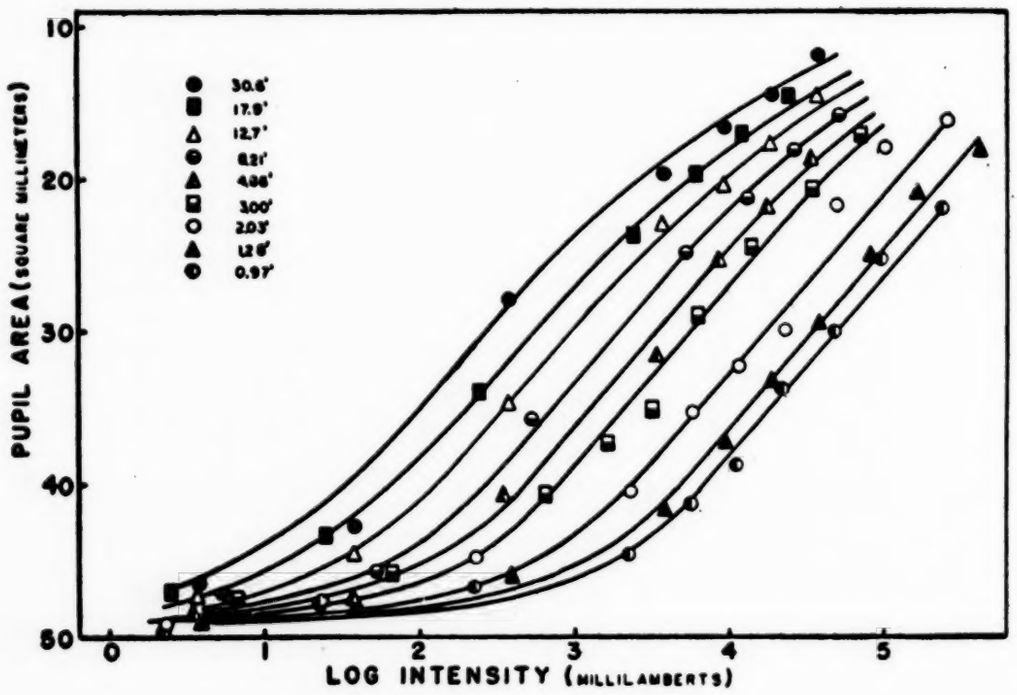

Fig. 1. Pupil area as a function of logarithm of the intensity for one subject (JIN) for foveal stimulation with different stimulus areas. The radii of the stimulus patches, expressed in minutes of visual angle, are listed in the key of symbols.

The results for one of our subjects (JIN) are plotted in Fig. 1. Here *pupil area*, in square millimeters, is plotted against the *logarithm of the intensity* in millilamberts for each of nine areas ranging in radius from 0.97′ to 30.6′ of visual angle. Each of the points in the figure represents the average value for pupil area as determined by twenty readings with the exception of the lowest *log intensity* value for each area. The latter points represent average values determined by ten readings. No attempt has been made to draw the best fitting curve through each set of points. Parallel lines have been drawn through

the points falling in the intermediate range of intensities. However it is apparent from the figure that these curves differ very little, if at all, from the best fitting curves.

Figure 2 emphasizes the parallelism in the shape of the curves. Data for two subjects (JIN, IJB) are plotted. This plot has been obtained by arbitrarily selecting one curve (the curve obtained following stimulation by an area of radius 0.97′ of visual angle) and by shifting each of the other curves a constant amount to the right such

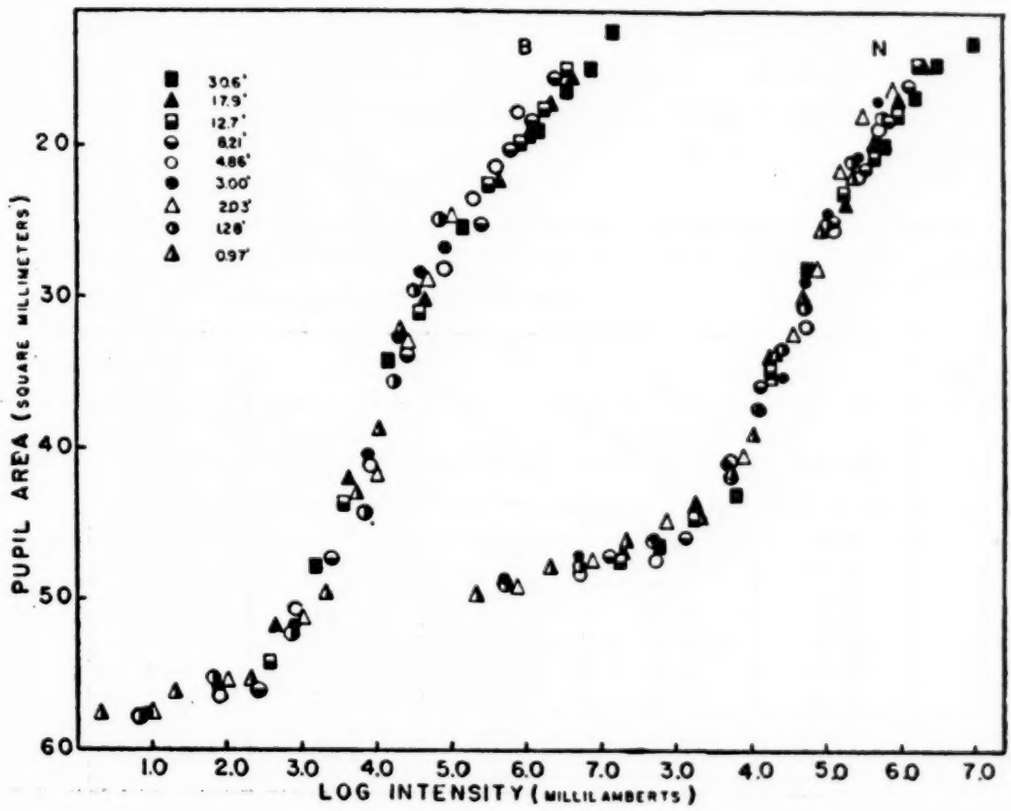

FIG. 2. Pupil area as a function of the logarithm of the intensity for two subjects (JIN, IJB) following foveal stimulation. In this figure the curve for one stimulus area for each subject has been arbitrarily selected and the remaining curves shifted along the abscissa until they overlap the selected curves.

that it overlaps the selected curve. The degree of parallelism in the original data is indicated by the relatively little scatter of the points when this is done.

The variability of most of the means plotted in Figs. 1 and 2 has been determined. Critical ratios have been calculated for the differences between mean values for areas adjacent in size, at comparable intensities. While the critical ratios that have been computed are not all statistically significant, they indicate that the differences found between the means, at comparable intensities, for areas adjacent in size are much greater than would be expected by chance alone. With one exception (critical ratio equals 0.22) the ratios in

a random sample indicate that in at least 98 chances out of 100 the differences found between the means are real differences. Furthermore the fact that the mean values for pupil area are adequately described by smooth curves drawn through the data, as shown in Fig. 1, indicates that there are true differences in pupil measurements obtained following stimulation by different areas.

It has been pointed out that an hypothesis of the area-intensity relation has been applied by Graham, Brown and Mote (**6**) and Graham and Bartlett (**4**) to absolute intensity thresholds. Graham and Bartlett (**5**) have more recently applied the formulation to differential thresholds. It is desirable to apply this formulation to another index of visual excitation, and especially to an index of

TABLE II

FOVEAL DETERMINATIONS—OBSERVED AND CALCULATED VALUES OF LOG *I*

Log Radius (Minutes)	Log Intensity (Millilamberts)					
	JIN		IJB		ABW*	
	Observed	Calculated from Equation (3)	Observed	Calculated from Equation (4)	Observed	Calculated from Equation (5)
1.49	2.20	2.34	1.72	1.84	0.78	1.03
1.25	2.52	2.57	2.05	2.10	1.30	1.38
1.10	2.72	2.74	2.30	2.28	1.62	1.63
0.91	3.00	2.96	2.61	2.55	1.96	1.95
0.69	3.22	3.27	2.92	2.89	2.46	2.35
0.48	3.51	3.58	3.21	3.26	2.64	2.76
0.31	3.90	3.86	3.66	3.61	3.16	3.12
0.11	4.26	4.23	4.04	4.06	3.56	3.56
−0.01	4.40	4.47	4.30	4.36	3.76	3.83

* For one level only (Pupil area equals 48 sq mm).

various levels of response. This may be done with pupil measurements by arbitrarily selecting various levels of pupillary response and treating the data in terms of the formulation.

As indicated in Figs. 1 and 2 the curves obtained by plotting *pupil area* against *logarithm of the intensity* for different sized stimulus areas are approximately parallel. Thus if the formulation fits for one level of response it should fit for all levels. Furthermore the curves may be shifted a constant amount and made to superimpose (as in Fig. 2) by adding a constant to the obtained log *I* values for each stimulus area. The relationship between the curves can now be expressed in terms of the values of the constants required to make the curves superimposable. Any log intensity value on one of the curves may be selected and the constants describing the relation of the other curves to the selected curve subtracted from it. The re-

sulting values will then describe the relation between all the curves at the level of response corresponding to the selected log intensity value. Since the curves are parallel the new values in reality describe the relation between the curves at any level of response. These values have been determined for two of the subjects (JIN, IJB). The level chosen for making these determinations is arbitrarily selected at 35 sq mm of pupil area.

Data for one subject (ABW) are so variable that it is impossible to describe his results by parallel curves and thus treat them in a

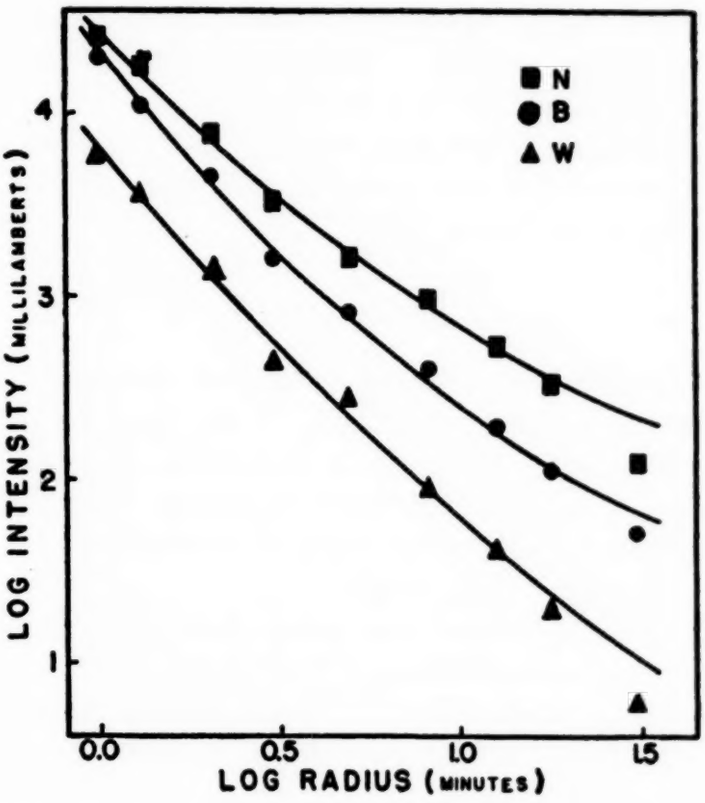

FIG. 3. Logarithm of the intensity necessary to produce a constant pupillary response to foveal stimulation as a function of the stimulus radius. The points represent observed values obtained for three subjects. The curves drawn through the data are computed from equations *3*, *4*, and *5*.

manner comparable to that used for the other subjects. However it seems advisable to attempt to fit the formulation to his data. Consequently one level of response is selected (pupil area equals 48 sq mm) and the log intensity values necessary to produce a pupil of this size for the different stimulus areas determined.

Table II presents the values obtained when the data are treated in this way. The observed *log I* values for two of the subjects are independent of the level of the response. The *log I* values for the remaining subject are obtained for only one level (pupil area equals 48 sq mm). The radii of the stimulus areas are presented, as in

Table I, in terms of minutes of visual angle. This makes it possible to compare data obtained with our subjects with the results of other experiments.

Figure 3 is a plot of the data presented in Table II. As the area of stimulus increases the intensity necessary for constant pupil constriction decreases. The relationship for two subjects is non-linear and the slope decreases as one proceeds from small to large areas. The intensity necessary for constant pupil constriction approaches a limiting asymptotic value at the largest areas. This relationship has been found for threshold intensities as well [Löhle (**9**), Graham, Brown, and Mote (**6**)]. The individual points in the figure are the observed log intensity values. The curves drawn through the points are theoretical and will be discussed later. The theoretical curve drawn through the data for one subject (ABW) also approaches an asymptote. However, a straight line describes the data as well and more will be said concerning this.

B. Periphery

Table III presents the averaged results obtained on each of two subjects for peripheral stimulation. With the exception of five instances for each subject, as noted in the table, twenty determinations of pupil area are available for each of eleven stimulus areas over a range of approximately five log units of intensity. The areas range from 3.21′ to 196.0′ of visual angle.

It is quite apparent from this table that constriction is obtained following peripheral stimulation. The pupil appears to constrict to about the same size as it does for foveal stimulation. However, as has been pointed out, for the peripheral determinations the subject is seated closer to the stimulus areas, and these areas are larger than for the foveal determinations. The quantity of light entering the eye is thus greater in the peripheral determinations even though the brightness of the stimulus areas is the same. Regardless of the greater quantity of light entering the eye at the higher levels of intensity the pupillary constriction to peripheral stimulation is less than that following foveal stimulation. This is not what one would expect to find in terms of intensity thresholds. The much lower intensity thresholds for the periphery of the eye would lead one to believe that a lesser intensity of stimulating light would be required to produce constriction following peripheral stimulation than would be required for constriction following foveal stimulation.

The nature of the variability of the means for the peripheral determinations has been determined in part. Critical ratios have been calculated for the mean values of several adjacent areas at

comparable intensities of stimulating light. The critical ratios obtained for the peripheral data are, in general, smaller than those obtained for foveal data but with one exception (critical ratio equals

TABLE III

PUPIL AREAS FOR DIFFERENT AREAS OF STIMULUS IN THE PERIPHERY

Radius in Minutes of Visual Angle	Log Intensity in Millilamberts	JIN		IJB	
		No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)
196.0	−0.80	20	43.90	20	46.07
	0.20	20	36.06	20	36.24
	1.20	20	25.44	20	26.65
	2.20	20	18.02	20	20.80
	3.20	20	14.79	20	17.19
	3.60	20	13.51	20	14.96
	4.20	20	12.32	20	13.52
137.0	−0.73	20	45.02	20	50.06
	0.27	20	39.65	20	39.94
	1.27	20	29.32	20	29.94
	2.27	20	20.22	20	22.91
	3.27	20	15.67	20	18.57
	3.67	20	13.91	20	16.19
	4.27	20	13.02	20	14.14
100.0	−0.20	20	46.97	20	48.93
	0.80	20	35.75	20	33.94
	1.80	20	25.91	20	25.69
	2.80	20	19.56	20	20.61
	3.80	20	16.13	19	16.46
	4.20	20	15.28	19	15.83
	4.50	20	14.82	20	15.87
	4.80	20	13.74	20	14.97
59.0	−0.40	20	48.11	20	53.31
	0.60	20	38.81	20	40.41
	1.60	20	30.41	20	30.32
	2.60	20	22.45	20	22.57
	3.60	20	17.48	20	18.53
	4.00	20	15.90	20	17.06
	4.30	20	15.17	20	15.67
	4.60	20	15.11	20	15.38
42.0	−0.22	20	48.36	20	53.40
	0.78	20	40.71	20	41.85
	1.78	20	31.51	20	30.43
	2.78	20	23.62	20	22.90
	3.78	20	17.42	20	19.15
	4.18	20	15.83	20	16.80
	4.48	20	15.29	19	15.14
	4.78	20	14.71	20	15.54
27.0	−0.07	20	48.87	20	53.97
	0.93	20	42.00	20	44.23
	1.93	20	34.40	20	32.74
	2.93	20	25.12	20	24.28
	3.93	20	18.93	20	19.68
	4.33	20	16.91	20	17.80
	4.63	20	15.90	20	17.03
	4.93	20	14.88	20	16.08

TABLE III—*Continued*

Radius in Minutes of Visual Angle	Log Intensity in Millilamberts	JIN		IJB	
		No. of Readings	Ave. Pupil Area (sq mm)	No. of Readings	Ave. Pupil Area (sq mm)
16.0	−0.25	20	49.06	20	54.64
	0.75	20	44.13	20	45.72
	1.75	20	37.72	18	33.78
	2.75	20	29.43	20	26.95
	3.75	20	21.36	20	22.20
	4.15	20	18.27	20	19.40
	4.45	20	16.59	20	17.55
	4.75	20	15.59	20	17.37
10.0	−0.97	10	51.78	10	54.50
	0.03	20	49.82	20	53.42
	1.03	20	44.66	20	44.58
	2.03	19	36.77	20	33.73
	3.03	20	28.39	20	24.26
	3.43	20	24.50	20	21.67
	3.73	20	21.86	20	20.02
	4.03	19	20.50	20	19.61
6.62	−0.43	10	50.70	10	55.15
	0.57	20	49.42	20	53.76
	1.57	20	44.43	20	44.97
	2.57	20	38.40	20	35.17
	3.57	20	29.36	20	26.49
	3.97	20	24.69	20	23.04
	4.27	20	21.28	20	21.16
	4.57	20	19.78	20	19.16
4.24	−0.21	10	50.91	10	55.15
	0.79	20	49.20	20	55.55
	1.79	20	45.14	20	48.15
	2.79	20	39.38	20	39.37
	3.79	20	30.72	20	27.91
	4.19	20	26.00	20	24.66
	4.49	20	23.33	20	22.24
	4.79	20	20.49	20	20.91
3.21	−0.45	10	51.83	10	55.84
	0.55	20	51.92	20	56.43
	1.55	20	49.44	20	52.96
	2.55	20	45.04	20	45.01
	3.55	20	39.55	20	37.57
	3.95	20	35.93	20	32.47
	4.25	20	31.79	20	29.78
	4.55	20	29.78	20	26.53

0.32) the ratios indicate that in at least 80 chances out of 100 the differences found between the means for adjacent areas are real differences.

In treating the peripheral data it is desirable to see if the same formulation applies at all levels of response as for the foveal data. The method for testing this is the same as that already used for the foveal data. Since the curves are parallel a formulation that fits the data at one level should fit the data at any level of response.

The curves describing the data presented in Table III can be made to superimpose by adding a constant to the *log I* values for each of the stimulus areas. These constants can then be used to describe the relation between the data obtained for different stimulus areas. Having selected a *log I* value on one of the curves these constants may be subtracted from this value. The resulting values will describe the relation between all the curves at the level of response corresponding to the selected *log I* value. Since the curves obtained for the peripheral data are parallel, as found for the fovea, and thus superimposable, the values thus obtained describe the relation between the curves at any level of response. The level selected for making these determinations is 35 sq mm for one subject (JIN) and 32 sq mm for another subject (IJB).

TABLE IV

PERIPHERAL DETERMINATIONS—OBSERVED AND CALCULATED VALUES OF LOG *I*

Log Radius (Minutes)	Log Intensity (Millilamberts)			
	JIN		IJB	
	Observed	Calculated from Equation (6)	Observed	Calculated from Equation (7)
2.29	0.26	0.46	0.68	0.84
2.14	0.64	0.67	1.08	1.03
2.00	1.01	0.88	1.24	1.20
1.77	1.25	1.23	1.46	1.50
1.62	1.56	1.48	1.74	1.71
1.43	1.92	1.80	1.96	1.99
1.20	2.18	2.21	2.18	2.34
1.00	2.37	2.59	2.34	2.66
0.82	2.91	2.94	2.90	2.96
0.63	3.31	3.34	3.42	3.30
0.51	4.00	3.60	4.00	3.52

Table IV presents values obtained for any level of response for the two subjects. In Fig. 4, which represents the data of Table IV, the *logarithm of the intensity* is plotted against the *logarithm of the radius* of the circular stimulus area. The points denote the observed *log I* values, while the curves drawn through the points are theoretical and will be described later. The theoretical curves fail to fit the data adequately. For the foveal determinations (Fig. 3) the relation between *log I* and *log R* is curvilinear and the slopes of the curves are found to decrease as one proceeds from small to large areas. In the peripheral data this does not seem to be the case. While the intensity necessary for constant pupil constriction must approach a limiting asymptotic value at some stimulating area, it does not appear to do so with the areas and intensities used in the present investigation.

This does not agree with the threshold intensity relationship found by others (**9**, **6**).

Some preliminary measurements have been made following monocular stimulation. A peculiar cusp appears in the curve when the data are plotted as are the peripheral data in Fig. 4. When *log I* values are plotted against *log R* a straight line describes the data obtained with large areas (radius subtending a visual angle from 27′

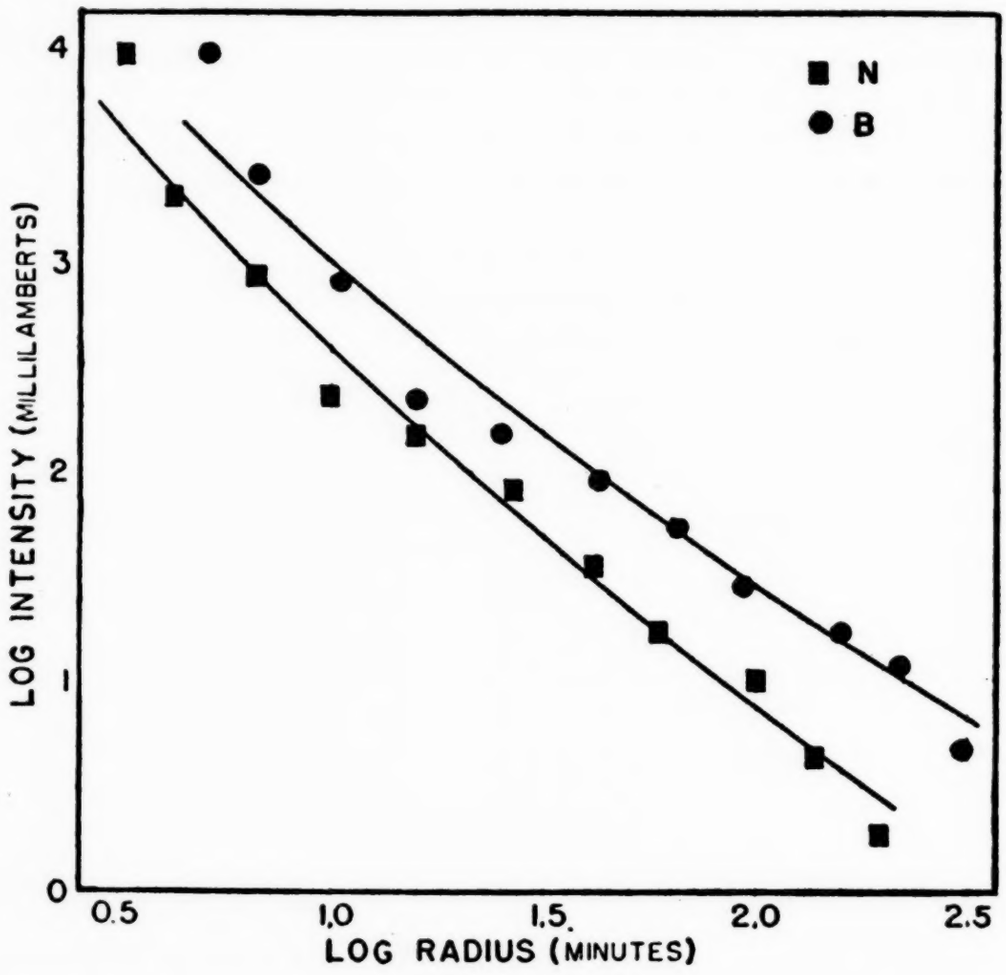

FIG. 4. Logarithm of the intensity necessary to produce a constant pupillary response to peripheral stimulation as a function of the stimulus radius. The points represent observed values obtained for two subjects. The points for one subject (B) have been shifted 0.2 log units to the right along the abscissa. The curves drawn through the data are computed from equations *6* and *7*.

to 196′). The points for the smallest area (3.21′ visual angle in radius) likewise fall on this line. The *log I* values corresponding with radii subtending a visual angle in minutes of 4.24, 6.62, 10 and 16 are less than one would expect from the rest of the data. These intensity values would have to be approximately 0.15 log units greater in order to be described by the curve describing the rest of the monocular data. More measurements will have to be made before it is

certain whether this apparent anomaly is inherent in the data or the result of some artifact.

Reeves (**10**) has presented evidence showing that over the range of ordinary brightness for continuous illumination the closing of one eye markedly increases the diameter of the pupil. We might expect, then, that the pupil diameter would be greater after monocular stimulation by a given intensity of light for 1″ than it would be after binocular stimulation by the same intensity. The data we have obtained do not show this to be the case. Pupil constriction to binocular stimulation is no greater than that following monocular stimulation. This discrepancy may be attributed to a differential effect in the dilatation of the pupils to decreased illumination of one eye and the constriction of the pupils to brief stimulation of either or both eyes.

Discussion

Pupil measurements offer a new index of visual excitation. Furthermore if one uses pupillary constriction as a measure of excitation one may use various constant levels of response. It is desirable to compare our data with those obtained by Graham, Brown and Mote (**6**) and to examine the area-intensity relation found here in terms of their formulation. The assumption is made that the minimal energy required for a constant response, such as the absolute threshold in their experiment, is determined at the center of a circular area and that other parts, although excited subliminally, make a contribution to the effect, E, at the center. Then the intensity effect at the center is

$$E = k_1 e \int_0^{2\pi} \int_0^R \frac{r dr d\theta}{r^p} \qquad (1)$$

where R is the radius of the circle, k_1 a constant of proportionality, e a constant intensity effect in each elemental area, r the radius of each elemental area, and p some power to which e is raised. If the assumption is made that e is proportional to *log* I($e = k_2 \log I/I_0$) this equation, on integration, becomes

$$\text{Log } I/I_0 = CR^{p-2} \qquad (2)$$

where $C = E\left(\frac{2-p}{2k_1k_2}\right)$. With the equation in this form it is possible to test for the agreement between theory and data. In order to evaluate the constants in the equation it is necessary to take logarithms on both sides. Then a plot of the *log log* I/I_0 against *log* R should give a straight line with a slope $p - 2$ and an intercept of *log* C if the theory fits the formulation. The value *log* I_0 may be

determined from the *log I* vs. *log R* plot and is the asymptote of the curve on the *log I* axis.

Figure 5 is a plot of our foveal data treated in this manner. The curve for one subject (IJB) is shifted 0.3 log units to the right along the abscissa. Except for one point in each set of data the values are well described by a straight line.

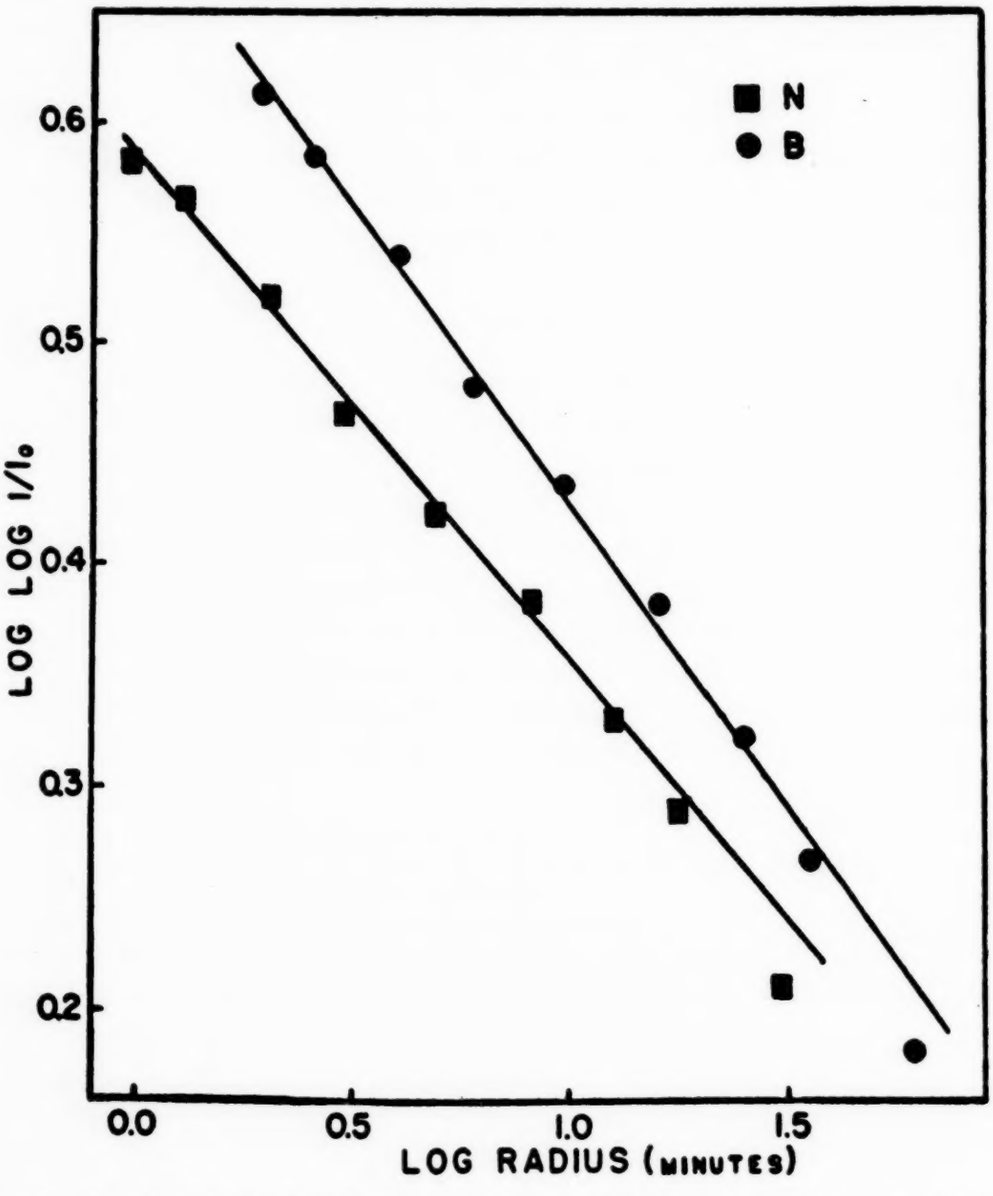

FIG. 5. Log log I/I_0 for foveal determinations as a function of stimulus radius for two subjects (JIN, IJB). Log I_0 is determined from Fig. 3. It is the asymptote of the curve on the log I axis. One curve (B) is shifted 0.3 log units to the right along the abscissa.

Figure 6 represents the same treatment of data for peripheral determinations. In this case since the slopes of the curves describing the data are the same for both subjects (−0.11), the curves have been superimposed by lowering the curve describing the data for one subject (JIN) 0.07 units along the ordinate. The curves describing

the data have been determined by the method of averages. While the curves do describe the data, they do not do so as adequately as for the foveal data. The peripheral data for the two subjects deviate systematically from the curves drawn through the data.

When the constants for pupillary data, obtained following foveal stimulation, are evaluated, the following expressions describe the data. For one subject (JIN)

$$\text{Log } I/I_0 = 3.87R^{-0.23} \tag{3}$$

where $log\ I_0 = 0.58$.

For another subject (IJB)

$$\text{Log } I/I_0 = 4.13R^{-0.27} \tag{4}$$

where $log\ I = 0.20$.

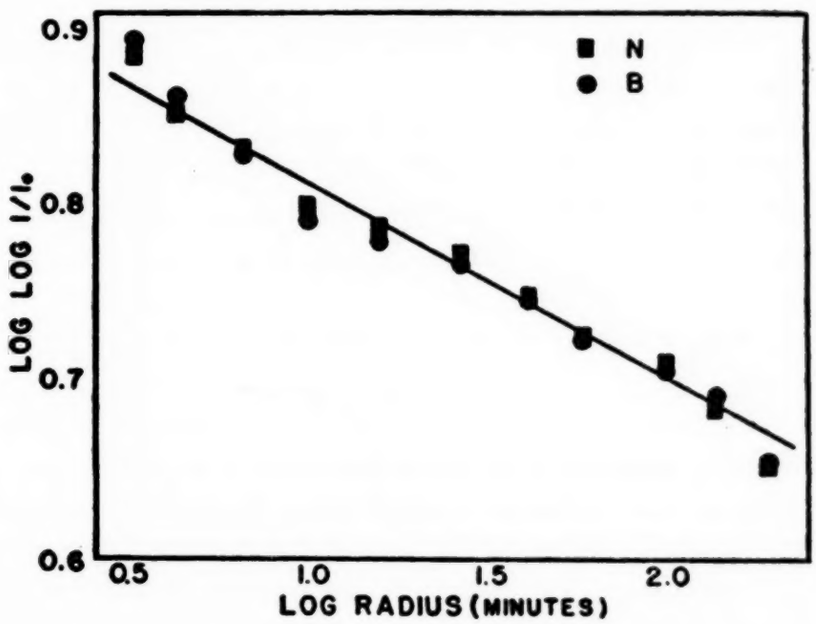

FIG. 6. Log log I/I_0 for peripheral determinations as a function of the stimulus radius for two subjects (JIN, IJB). Log I_0 is determined from Fig. 4. It is the asymptote of the curve on the log I axis. The points for one subject (N) have been lowered 0.07 units along the ordinate.

The values of two of the constants above are quite comparable. On the other hand the asymptotic values differ to a greater extent.

For one subject (ABW) the constants differ considerably from those given above. The relation describing his data is expressed by the equation

$$\text{Log } I/I_0 = 7.31R^{-0.14} \tag{5}$$

where $log\ I_0 = -3.5$.

Data for this subject, as mentioned elsewhere, are treated somewhat differently. The formulation has been applied to only one level of response, where pupil area equals 48 sq mm. In the case of the other subjects the formulation is applied to all levels of excitation. At present we cannot account for the deviations on the part

of this subject. The only explanation appears to lie in the variability and irregularity of the responses made.

When the constants are evaluated for the peripheral determinations the following values are obtained. For one subject (JIN)

$$\text{Log } I/I_0 = 9.84R^{-0.11} \tag{6}$$

where *log* $I = -5.05$.

For another subject (IJB)

$$\text{Log } I/I_0 = 8.39R^{-0.11} \tag{7}$$

where *log* $I = -3.85$.

Here again, except for the asymptotic constant *log* I_0 the constants obtained for the two subjects are comparable. However it is to be noted that the slope constants in the case of the peripheral determinations are about half as large as those obtained for the foveal determinations.

The expressions obtained by Graham, Brown and Mote (**6**) for intensity thresholds for white light, when constants are determined in the manner described above, are

$$\text{Log } I/I_0 = 1.61R^{-0.51} \tag{8}$$

for the fovea, where *log* $I_0 = -2.90$ and

$$\text{Log } I/I_0 = 6.92R^{-0.54} \tag{9}$$

for the periphery, where *log* $I_0 = -5.95$.

The results of the present experiment show that the slope constants for the foveal data are quite comparable for two subjects. Likewise the constants, except the asymptotic constants, obtained for the peripheral data for two subjects are comparable. However these constants are about half as large as those obtained for the foveal determinations. This does not agree with the findings of Graham, Brown and Mote (**6**). They obtained nearly the same values for the slope constants for both foveal and peripheral absolute threshold determinations with white light. For the fovea the slope constant, $p - 2$ has a value of -0.51. The curve drawn through the points for the peripheral data has a slope of -0.54. Later, Graham and Bartlett (**4**), using red and violet light, obtained slope constants of -0.50 and -0.60 for foveal and peripheral data respectively. The formulation, when applied by Graham and Bartlett (**5**) to foveal intensity discrimination data, requires a slope of unity.

In Table II the *log I* values calculated from equations 3, 4 and 5 are presented for foveal determinations. The curves drawn through the experimental points in Fig. 3 represent the theoretical values calculated from these equations. An examination of the figure and

the table shows that these equations offer an adequate description of the foveal data. The questionable values appear to be the points determined for the largest areas. Graham, Brown and Mote found this to be true for threshold determinations as well. They interpret a greater sensitivity for the large areas than would be expected theoretically in terms of a sampling of rods.

As they point out, histological findings of Rochon-Duvigneud (**12**) show that rods are present in the foveal area beyond the units of the central bundle of cones which includes about 35′ of visual angle. When flashes of red light which would be expected to stimulate the rods little, if at all, are used, the experimental points for these areas fall directly on the theoretical curves [Graham and Bartlett (**4**)]. The presence of rods in the margin of the fovea leads one to anticipate deviations from theoretical expectations in our experiment where large areas and white light are used.

In Table IV the calculated *log I* values are presented for peripheral determinations. They are calculated from equations 6 and 7. While the foveal data for two subjects are such as to preclude any simple power function of the form $A^kI = C$, such as Wald (**13**) has suggested as an adequate description of the area-intensity function, the foveal data for one subject and the peripheral data for two subjects are subject to such an interpretation.

The fact that, when the data obtained in the present investigation are treated in the manner suggested by Graham's formulation, a new set of values for the constants is obtained needs to be considered. In experiments where this formulation has been applied different values have been obtained. The differences found in the value of the constant, *C*, has no special significance. The differences found between the value of *C* for pupillary measurements and that for threshold determinations may well be interpreted in terms of the wide differences in the range of intensities used in the two experiments. Much greater intensities are used in pupillary determinations than are used in threshold measurements.

Failure to find a closer correspondence in the values determined for the slope constants offers a more serious difficulty. Graham and Bartlett (**5**), in commenting on the discrepancy between the values obtained for absolute and differential thresholds, state:

> The value of $2 - p$ in the two groups of experiments remains a serious discrepancy, and further critical experimentation will be required before the difficulty it presents can be resolved.

The present experiment yields still different values for $2 - p$ than in the threshold studies. That there is some as yet unconsidered factor playing a role in the visual process seems evident. It is quite conceivable that an inhibitory factor is involved which exerts an

influence on e, the constant intensity effect in each elemental area. Ultimately in any theory involving a gradient of effect from the margin of the stimulated area inward, with the greatest effect at the center, it may be necessary to include some concept of inhibition.

That a formulation which adequately describes the area-intensity relation at one level of response—the threshold level—fails to describe adequately data obtained at other levels is not surprising in view of the results obtained in an earlier investigation. In a study of the retinal action potentials of the frog eye during dark adaptation Riggs (**11**) has determined as a function of time in the dark the logarithm of the intensity required to produce a b-wave of constant height. When a low level of response is used, a curve of dark adaptation is obtained comparable to curves based on human threshold determinations. At higher levels of response (b-waves of greater height) curves of different shape are obtained.

Failure to find that Graham's formulation describes the data at all levels has led us to apply the formulation postulated by Wald. Wald (**13**), who accounts quantitatively for characteristic variation in the visual threshold, with variation in field area in terms of the statistical properties of the retina, has fitted an equation of the form A^kI = Constant to his own peripheral data and to the data of Abney and Pieron for the fovea. While the foveal data for two subjects in the present investigation is such as to preclude any simple power function of the form suggested by Wald as an adequate description of the area-intensity relation the peripheral data for two subjects and foveal data for one subject are open to such an interpretation.

Wald's data are adequately described by the expression $A^kI = C$ or, expressed logarithmically, $\log I = -k \log A + \log C$. Wald found the slope constant, $-k$, for peripheral data obtained 15° above the fovea to be 0.33. With the stimulus area located 25° above the fovea the slope constant is 0.54. The peripheral determinations in the present investigation are made with the areas 35° to the nasal side of the fovea. For these data the equation

$$\text{Log } I = -0.73 \log A + 2.0 \qquad (10)$$

describes approximately the results for one subject (IJB) while the expression

$$\text{Log } I = -0.88 \log A + 1.9 \qquad (11)$$

describes the results for another subject (JIN). The constant, $-k$, appears, then, to vary with the peripheral region stimulated and increases as one goes from the fovea toward the periphery. This is true for the constants obtained by Wald for areas 15° and 25° above the fovea and by us for areas centered 35° in the periphery. At 15°

above the fovea $-k = 0.33$, at 25° above the fovea $-k = 0.54$, and at 35° in the periphery $-k = 0.73$ and 0.88 for two subjects.

Although the above formulation describes the foveal data for one subject (JIN) as well as does Graham's formulation it does not as adequately describe the data for the second subject (IJB). Values calculated for this subject in terms of Wald's formulation correspond less closely to the observed values than do the calculated values obtained by Graham's formulation.

With one subject (ABW), for whom the foveal data in our experiment are available, the constants differ considerably from those obtained with other subjects. It is possible to describe the data obtained with this subject by the equation

$$\text{Log } I = -0.97 \log A + 1.95 \qquad (12)$$

The slope constants obtained by Wald to describe the threshold data of Abney and Pieron are −0.85 and −0.88 respectively. It thus appears that Wald's formulation, in terms of the statistical properties of the retina, when applied to our foveal data, yield, for one of three subjects, a slope constant comparable to that obtained by Wald (**13**).

When the above findings are considered it appears questionable that either hypothesis is adequate without modification or extension to describe excitation at any level in the human eye. The procedure used in the present investigation differs markedly in one respect from other investigations. In previous experiments threshold or minimal excitation has been used as a measure of the sensitivity of the eye. The present study has involved intensities of light a thousand times greater than the threshold values. It is feasible that a formulation accounting for threshold excitation would not account for excitation effects due to great intensities of light. A new formulation may be required to do so. The linear relationship found between the logarithm of the intensity necessary for constant pupil constriction and the stimulus area suggests that this might be necessary. In studies of the absolute threshold a curvilinear relationship between logarithm of the intensity and logarithm of the stimulus area has been obtained where sufficiently large stimulus areas have been used.

Summary

1. An apparatus and procedure have been described which made it possible to obtain measurements of the pupil of the human eye following stimulation by different areas and intensities of stimulating light.

2. For the fovea, as the stimulus area increases the intensity necessary for constant pupil constriction decreases. The relation between logarithm of the intensity and logarithm of the radius of the stimulus area for two subjects is curvilinear and the slopes of the

curves describing the data decrease as one proceeds from small to large areas. The logarithm of the intensity necessary for constant pupil constriction to 1″ flashes of light approaches a limiting asymptotic value. This is not true for one subject, where the relation between the logarithm of the intensity necessary for a constant pupil constriction and the logarithm of the radius of the stimulus area is a linear one.

3. For peripheral stimulation, as the stimulus area increases the intensity necessary for constant pupil constriction decreases. However, with the areas and intensities used in the present investigation, the intensities necessary for constant pupil constriction fail to approach a limiting asymptotic value and a straight line best describes the relation between logarithm of the intensity and logarithm of the radius of the stimulus area. This is true for both monocular and binocular stimulation.

4. A quantitative analysis of the area-intensity relation is given in terms of two different formulations. When measurements of pupil area are used as an index of visual excitation neither formulation is entirely adequate in explaining the area-intensity relation at all levels of response. Formulations accounting for excitation at the threshold level will have to be modified or extended to include excitation at higher levels.

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THE EFFECT OF SPACING OF TRIALS ON THE ACQUISITION AND EXTINCTION OF A CONDITIONED OPERANT RESPONSE [1,2]

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In the field of learning, it has been known for many years that more rapid learning results when trial intervals are long than when successive trials are given rapidly. The classical problem of massed vs. distributed practice has received much attention and has resulted in a nearly unanimous experimental agreement as to the greater efficiency of 'distributed' trials. The literature on this problem has been well summarized by Hunter (**7**) and by Woodworth (**13**).

The results of the learning experiments are not directly applicable to the problems of the present paper, because with few exceptions the trial intervals used have been hours or days. An adequate hypothesis to account for these facts must take into account the process of forgetting. The problem with which we are concerned, however, involves the measurement of the effect of spacing of trials on the entire course of acquisition and extinction. Since the time intervals employed are short, it is assumed that within the time employed for a single set of measurements the amount of forgetting which occurs is negligible. Experiments comparable to this are to be found in the field of conditioned reflexes.

In a study of conditioned galvanic skin responses in children, Jones (**8**) found that massed presentation of stimuli led to a temporary diminution of responses to the conditioned and unconditioned stimuli, with full recovery on the following day. In establishing conditioned breathing responses in white rats, Schlosberg (**12**) found that acquisition proceeds more rapidly if 25 paired stimulations per half-hour session are used, rather than 200. Calvin (**1**) studied the effect of spacing trials on the acquisition of conditioned eyelid responses in man. Using three different intervals between trials—20 seconds, 6.7 seconds, and 3.3 seconds—the rate of acquisition was found to be greatest with the longest interval. With this same response, Humphreys (**6**) obtained a more rapid acquisition with a 1-minute trial interval than with a 30-second trial interval.

[1] This is one of a series of three articles presented as a thesis to the faculty of the Graduate School of Brown University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Psychology, October, 1940.

[2] The author is indebted to Professor C. H. Graham of Brown University, under whose direction the present research was carried out.

The effect of trial intervals upon the rate of extinction has been investigated by Hilgard and Marquis (**3**), who found an extremely slow extinction of the conditioned eyelid response in one dog when trials were given at the rate of 10 every other day. A more rapid extinction was obtained in a group having 60 extinction trials every day. Two experiments by Porter appear to contradict the Pavlovian prediction that massed trials result in a more rapid extinction than spaced trials. In the first investigation (**10**) Porter found no significant differences in rate of extinction for the response in rats of running down a 20-foot alley, when trials were spaced at a few seconds, 5 minutes, and 10 minutes. In a second experiment (**11**) Porter studied the extinction of conditioned eyelid responses in 5 groups of human subjects, with trial intervals of 10, 20, 40, 80, and 180 seconds. Again in this experiment no significant differences between the rates of extinction were found under the five different conditions employed.

A phenomenon which has been shown to result from the massing of acquisition trials is the appearance of an initial rise, usually on the second trial, in the curve of extinction. Hovland (**5**) demonstrated this effect in the extinction of the conditioned galvanic skin response of human subjects. An initial rise in the curves of extinction appeared when acquisition trials followed each other closely and when extinction was begun immediately following the final reinforced trial. According to Hovland, these results are consistent with Pavlovian theory (*cf.* **9**). When massed training is used, a great deal of inhibition is built up, which depresses the initial level of extinction. As inhibition dies away, however, the response recovers in strength and increases on the second extinction trial.

The background of the present experiments lies in an earlier paper (**2**), which presents a quantitative formulation of the conditioning process. This description employs the factors of excitation and inhibition, the action of which variables is supposed to determine response strength during the acquisition and extinction of a conditioned response. For the purposes of the present investigation, it is sufficient to note that according to theoretical reasoning the effect of lengthening the interval between trials should be to allow more time for the more 'labile' process of inhibition to die away. The result of such spacing should therefore be to produce more rapid acquisition and slower or less complete extinction.

Another factor which may have to be taken into account, however, is that of reinforcement. The amount of reinforcement may not be simply proportional to the size or weight of the food reward. If the reinforcement provided by a piece of food of given size is spread out over varying intervals of time, as is the case when trial-intervals are varied, the possibility exists that the effectiveness of the reward may

be diminished as the interval is lengthened. It is hypothetically possible that the fundamental variable with regard to reinforcement is not the actual magnitude of the unconditioned stimulus, but its effect through time to the next trial. This has been termed its 'average stimulating effect' (**2**). In an actual experiment, if the size of the unconditioned stimulus is maintained constant, its average stimulating effect may be supposed to diminish as the trial interval is made longer. The assumption is that the influence of a given reinforcement upon a subsequent trial is reduced in effectiveness as the time interval increases.

In order to separate the action of these variables on the acquisition and extinction of a conditioned operant response, two experiments were performed. In the first, trial intervals alone were varied, and the size of the unconditioned stimulus was kept constant throughout. In the second experiment trial intervals were again varied, and an attempt was made to approximate a constant 'average stimulating effect of the unconditioned stimulus' (*i.e.*, $\frac{\text{Amount of food}}{\text{Interval between trials}} \approx \text{Constant}$) by allowing the animal to eat throughout the period spent in the food box.

Experiment I

Apparatus and Procedure

The apparatus used in these experiments has been described in a previous paper (**2**). It is an elevated runway, three feet long, with a starting box at one end and a food box at the other end. The measure of response employed is the latent period, which is defined as the time taken by the rat to leave the starting box, after the door is opened, before he starts on his way to food.

Forty-eight white rats, divided into six equal groups, took part in the experiment. Eleven additional animals were trained in the usual way, but were discarded when they failed to leave the starting-box within five minutes on the first trial of acquisition. Half of the animals of each group were run in the morning, half at night.

Each rat was given four preliminary training sessions on four successive days. On each training day the rat ran on a trial runway, resembling the one used in the experiment, for about 10 minutes without reinforcement. Following this the animal ate pieces of the experimental food in the food box for twenty minutes. On the fourth day the eating time was shortened to twelve minutes. Acquisition and extinction were measured on the fifth day, the interval between trials being ½ minute, 1 minute, 2 minutes, 3 minutes, 5 minutes, or 10 minutes, depending on the particular group to which the rat belonged.

To control any possible diurnal variations in motivation or general activity, measurements were made at the same trial interval on different rats in the morning and evening of each experimental day. In addition, age and litter differences were controlled. The effect of each trial interval was tested on different days within the space of two weeks. Thus, in any one experimental group, each rat tested in the morning and each rat tested in the evening is matched by a rat in every other group with respect to age (within a variation of two weeks) and litter (with one or two exceptions).

Acquisition was continued for 15 trials. Extinction followed at the same constant tria interval, and was continued until the criterion of a 3-minute latent period was reached. Regardless of the interval used, the reinforcement was always a small pellet of dog chow of constant size, weighing about 0.06 grams. When the ½-minute trial interval was used, the rat had just

TABLE 1

THE AVERAGE LOGARITHM OF THE LATENT PERIOD ON EACH OF 15 TRIALS OF ACQUISITION AND 5 TRIALS OF EXTINCTION FOR SIX GROUPS OF RATS, UNDER CONDITIONS IN WHICH REINFORCEMENT WAS PROVIDED BY A PIECE OF FOOD OF CONSTANT SIZE

Trials in these different groups were spaced at ½ minute, 1 minute, 2 minutes, 3 minutes, 5 minutes and 10 minutes.

Process	Trial	Log P. ½-min. Interval	A.D. log P.	Log P. 1-min. Interval	A.D. log P.	Log P. 2-min. Interval	A.D. log P.	Log P. 3-min. Interval	A.D. log P.	Log P. 5-min. Interval	A.D. log P.	Log P. 10-min. Interval	A.D. log P.
Acquisition	1	1.85	0.21	1.80	0.19	1.81	0.17	1.80	0.16	1.88	0.23	1.89	0.21
	2	1.44	.22	1.45	.23	1.36	.12	1.27	.17	1.32	.16	1.26	.18
	3	1.23	.20	1.15	.17	1.20	.11	1.16	.12	1.17	.15	1.14	.17
	4	1.18	.23	1.16	.18	1.18	.15	1.06	.12	1.09	.12	1.08	.13
	5	0.97	.33	1.17	.22	1.18	.14	1.00	.18	1.13	.15	0.99	.12
	6	0.94	.24	0.97	.25	1.06	.14	0.99	.13	0.91	.24	0.86	.11
	7	0.70	.27	0.87	.21	1.04	.17	0.95	.14	0.93	.15	0.82	.15
	8	0.66	.34	0.88	.24	1.02	.15	0.82	.20	0.82	.26	0.72	.15
	9	0.60	.38	0.71	.31	1.02	.15	0.85	.25	0.71	.28	0.62	.13
	10	0.52	.39	0.64	.36	0.94	.16	0.82	.22	0.73	.21	0.62	.15
	11	0.50	.21	0.60	.29	0.90	.13	0.77	.25	0.62	.25	0.51	.14
	12	0.49	.33	0.52	.37	0.89	.21	0.68	.23	0.65	.24	0.43	.15
	13	0.30	.24	0.38	.27	0.84	.17	0.68	.14	0.45	.25	0.39	.20
	14	0.22	.18	0.37	.32	0.73	.18	0.63	.21	0.40	.27	0.38	.14
	15	0.22	.18	0.33	.27	0.75	.29	0.55	.27	0.43	.28	0.35	.21
Extinction	1	0.23	.29	0.17	.16	0.79	.25	0.51	.31	0.42	.23	0.22	.15
	2	0.36	.16	0.53	.29	1.00	.24	1.03	.19	0.93	.33	0.91	.21
	3	1.17	.17	1.16	.31	1.28	.19	1.32	.22	1.21	.21	1.10	.24
	4	1.34	.17	1.30	.23	1.34	.18	1.33	.20	1.31	.23	1.29	.15
	5	1.35	.16	1.37	.29	1.51	.23	1.41	.17	1.39	.27	1.33	.19

time to finish eating this amount of food before he was transferred in the box to the starting position. With the longer intervals, the rat remained in the food box after consuming the food; he was placed in the starting position 10 seconds before the beginning of the next trial.

Results

Acquisition.—The average logarithm of the latent period on each trial of acquisition for the six groups of rats is given in Table 1, together with the average deviations of log latent period.

Figure 1 shows the acquisition curves for each of the six groups, the logarithm of the latent period being plotted against the trial.

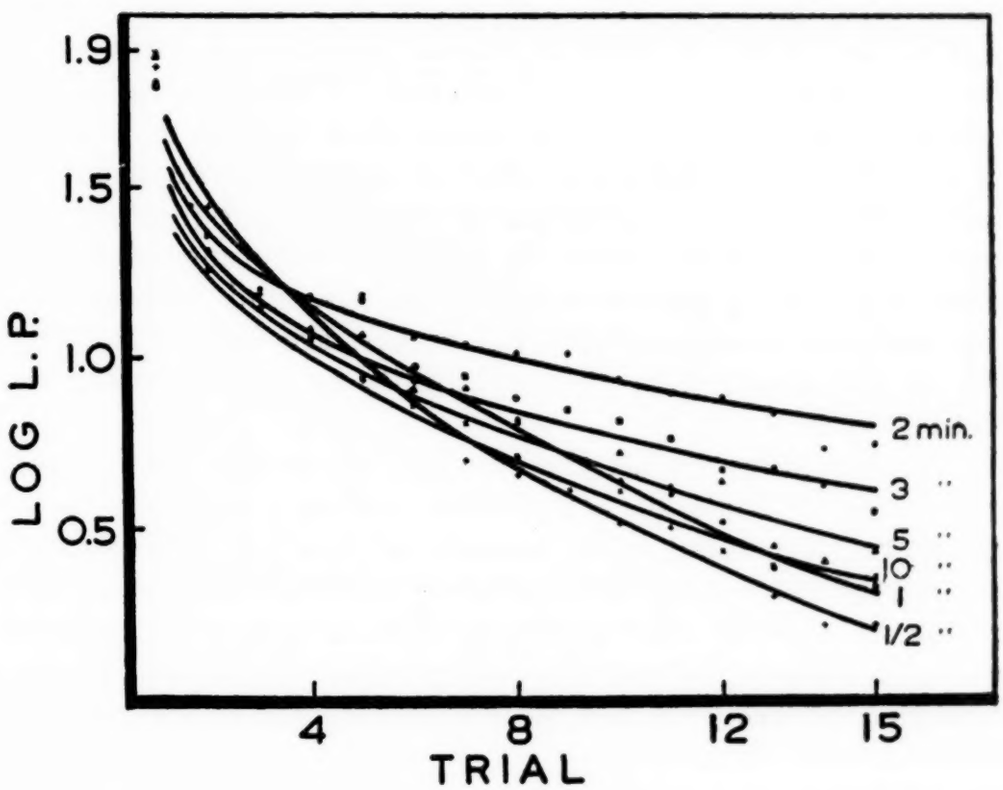

Fig. 1. The effect of spacing of trials on the curve of acquisition, when the reinforcement is a constant-sized pellet of food. The curves for the six trial-interval groups are drawn by inspection through the experimental points. Each point represents an average of values obtained from 8 animals.

For the ½-minute trial-interval group, the curve of acquisition starts with an average log latent period value of 1.85 (71 seconds) and reaches a log value of 0.22 (1.7 seconds) on the fifteenth trial. The group having a 1-minute interval between trials begins acquisition with a log latent period value of 1.80 (63 seconds) and proceeds to a value of 0.33 (2.1 seconds) on the fifteenth trial. In the 2-minute-interval group, acquisition starts with a log value of 1.81 (65 seconds) and attains a value of 0.75 (5.6 seconds) on trial fifteen. Acquisition in the group with 3-minute trial intervals starts with an average log latent period of 1.80 (63 seconds), and on the fifteenth trial reaches

a log value of 0.55 (3.6 seconds). The 5-minute-interval group has a log latent period of 1.88 (76 seconds) at the beginning of acquisition, and 0.43 (2.7 seconds) on trial fifteen. For the rats whose trials were spaced 10 minutes apart, the log latent period on the first acquisition trial is 1.89 (78 seconds) and on the fifteenth 0.35 (2.3 seconds).

It may be seen from Fig. 1 that the acquisition curves for the longer interval groups (2–10 minutes) have a steeper initial slope, up to the third acquisition trial. Following this, the curves for these groups exhibit a more rapidly decreasing rate than that of the two shortest-interval groups. The amount of decrease in rate after Trial 3 occurs in the following order for the six groups: 2-minute, 3-minute, 5-minute, 10-minute, 1-minute, ½-minute. Thus as acquisition proceeds, lengthening the interval between trials from ½ to 2 minutes is shown more clearly to have the effect of increasing the latent period, and from 2 minutes to 10 minutes, to produce a progressive decrease in latent period. On the fifteenth trial, the differences between the 2-minute and the ½-minute-interval groups, and between the 2-minute- and the 10-minute-interval groups are both significant according to the *t*-test [*i.e.*, the probability of chance occurrence is 1 percent].

The results indicate that the effect of increasing the interval between successive trials of acquisition, under conditions in which amount of reinforcement [*i.e.*, amount of food] is held constant, is to decrease the rate of acquisition up to a certain interval, and later to increase it. In our experiment the minimum rate occurs with the interval of 2 minutes between trials. From this minimum the rate increases progressively as the length of interval is increased to 10 minutes.

The existence of a minimum rate of acquisition with increasing intervals between trials has not been reported in studies of conditioned responses such as those of Calvin (1) and Humphreys (6) on the conditioned eyelid response in human subjects. Calvin found no difference in rate of acquisition between groups having trials spaced at 3.3 and 6.7 seconds, but he did find an increased rate with the longer interval of 20 seconds between trials. Humphreys found an increased rate when trials were spaced at 1 minute, over that which obtained with 30-second trial intervals. The occurrence of a minimum rate in our experiment is dependent upon the factor of reinforcement, as the results of Experiment II demonstrate. Further discussion of the problem is deferred until the data of that experiment are considered.

Extinction.—Table 1 presents the average logarithm of the latent period on each of five trials of extinction, with their average devia-

tions, for the six groups of rats. These data are plotted in Fig. 2 which shows the relation between the logarithm of the latent period and the number of extinction trials for each of the six trial-interval groups. The curves of extinction were drawn by connecting the actual experimental points.

The groups having ½-minute, 1-minute, 2-minute, 3-minute, 5-minute, and 10-minute intervals between trials begin extinction with average log latent period values of 0.23 (1.7 seconds), 0.17 (1.5 seconds), 0.79 (6.2 seconds), 0.51 (3.2 seconds), 0.42 (2.6 seconds), and 0.22 (1.7 seconds) respectively. The log latent period values of all groups approach each other more closely as extinction proceeds.

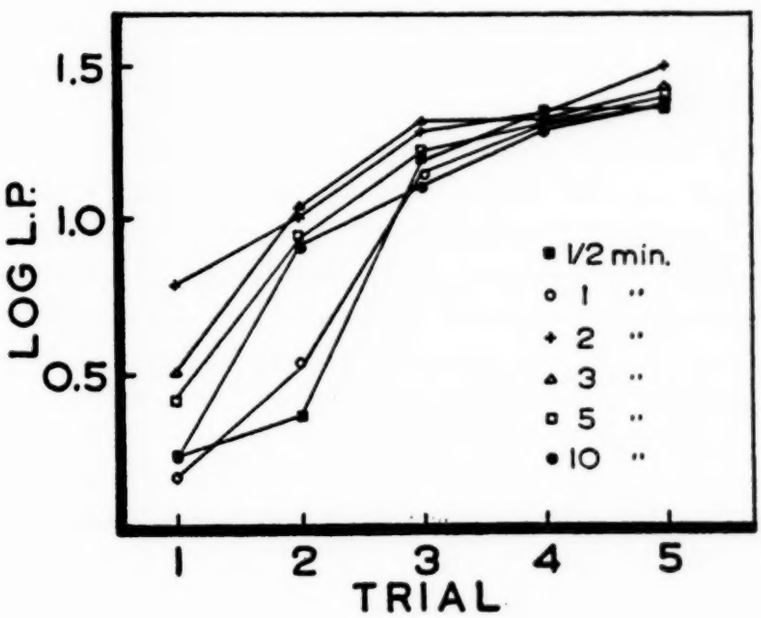

FIG. 2. The effect of spacing of trials on the course of extinction. The curves for the six trial-interval groups have been constructed by joining the experimental points. Each point represents an average of values obtained from 8 animals.

On the fourth and fifth trials there are no significant differences between the values for the six groups of animals. On the fourth trial, the average log latent period value of the six groups is 1.32 (21 seconds), and on the fifth trial, the value is 1.39 (25 seconds).

Two features of the curves of Fig. 2 should be emphasized. The first is the slight increase in latent period which occurs between trials one and two, in the case of the animals belonging to the ½-and 1-minute trial-interval groups. The group which had 2 minutes between trials also exhibits this characteristic to a slight extent. Although the ½-, 1-, and 10-minute groups begin extinction with nearly identical values of log latent period, the *t*-test indicates significant differences between the first two groups and the 10-minute group on the second extinction trial.

A second finding is illustrated by Fig. 2. The curve of extinction of each group begins at a level which corresponds approximately to the log latent period value on the final trial of acquisition. However, by the fourth trial of extinction, and continuing to the fifth trial, the differences in log latent period which obtain between the groups are not significant. Thus, although the groups having the shortest trial intervals begin extinction with latent period values below the remaining groups, the more rapid rate of extinction which is evidenced following Trial 2 enables them to reach the level of the other groups by the fourth trial.

The data reveal that when acquisition and extinction are carried out with intervals between successive trials of $\frac{1}{2}$- and 1-minute, there is a depression in the rate of extinction occurring on the second trial. This result is similar to one reported by Hovland (**5**) on the conditioned galvanic skin response, and called by him the 'inhibition of reinforcement.' In Hovland's study, a depression in the rate of extinction occurred on the second trial, when extinction followed immediately the massed presentation of stimuli during acquisition. In our experiment, the $\frac{1}{2}$-, 1-, and to a lesser extent the 2-minute intervals represent the massed presentation of stimuli during acquisition. When trials are spaced farther apart at the 3-, 5-, and 10-minute intervals, this depression in rate does not occur.

Following a slower rate of extinction on the second trial, in the groups with shorter trial-intervals, the rate increases so that by the fourth extinction trial the magnitude of the response is closely similar to that of the longer interval groups. These results seem to show that the course of extinction is slower in groups having more widely-spaced trial intervals during acquisition and extinction. In this respect they may be contrasted with the data of Porter's (**10**) experiments with rats on a straight alley, and with the conditioned eyelid responses of human beings. Both these studies indicated no difference in the rate of extinction with different spacing of extinction trials. The interpretation of the data of our experiment in this manner, however, is subject to the condition that the six groups began extinction at entirely different levels of response magnitude. These initial differences in the curve of extinction may obscure the relationship between trial intervals and rate of extinction, to some extent. Further evidence bearing upon this point is reported in Experiment II.

Experiment II

Apparatus and Procedure

In this experiment the same apparatus and general procedure were employed as in Experiment I. Acquisition and extinction were measured in five groups of twelve animals each; each group was given the usual preliminary training. As in the previous experiment, the procedure followed assured a control of diurnal variations and age and litter differences.

TABLE 2

THE AVERAGE LOGARITHM OF THE LATENT PERIOD ON EACH OF 15 TRIALS OF ACQUISITION AND 5 TRIALS OF EXTINCTION FOR FIVE GROUPS OF RATS, UNDER CONDITIONS IN WHICH EACH RAT WAS ALLOWED TO EAT FOR THE DURATION OF THE PERIOD SPENT IN THE FOOD BOX

Trials in these groups were spaced at ½ minute, 1 minute, 2 minutes, 3 minutes and 5 minutes.

Process	Trial	Intervals between Trials									
		½-min.		1-min.		2-min.		3-min.		5-min.	
		Log L.P.	A.D. log P.	Log L.P.	A.D. log P.	Log L.P.	A.D. log P.	Log L.P.	A.D. log P.	Log L.P.	A.D. log P.
Acquisition	1	1.76	0.23	1.72	0.21	1.68	0.21	1.73	0.19	1.72	0.22
	2	1.43	.15	1.31	.13	1.25	.14	1.17	.14	1.05	.13
	3	1.18	.23	1.23	.15	0.93	.17	0.82	.21	0.58	.16
	4	1.19	.19	1.08	.14	0.80	.13	0.66	.26	0.36	.27
	5	0.95	.22	0.96	.18	0.52	.13	0.48	.23	0.30	.23
	6	1.06	.22	0.86	.21	0.53	.16	0.42	.31	0.19	.22
	7	0.88	.16	0.86	.12	0.33	.19	0.31	.34	0.13	.17
	8	0.83	.28	0.84	.11	0.36	.17	0.29	.34	0.13	.14
Extinction	1	0.80	.22	0.78	.20	0.41	.26	0.37	.29	0.10	.14
	2	0.78	.23	0.92	.15	0.79	.15	0.83	.25	0.64	.20
	3	1.33	.14	1.23	.16	1.11	.18	1.08	.16	0.92	.14
	4	1.68	.28	1.42	.15	1.21	.13	1.28	.27	1.13	.19
	5	1.57	.18	1.48	.15	1.30	.17	1.41	.20	1.19	.21

The trial intervals used in this experiment were ½ minute, 1 minute, 2 minutes, 3 minutes, and 5 minutes. Eight trials of acquisition were followed by as many trials as were required for extinction to a criterion of a 3-minute latent period. For any group of animals the spacing between trials in both acquisition and extinction was held constant at one of the five intervals indicated above.

During acquisition, the rat ate small pellets of food in the food box throughout all but the final part of the interval between trials. Of this period the final ten seconds were spent in the starting box. A preliminary determination was made of the amount of food eaten by the average rat during each of the required intervals, and these amounts were placed in the food box before the start of each trial. The amount of food eaten by the rat during each ½-minute interval was 0.06 grams; during the 1-minute, 0.18 grams; during 2 minutes, 0.56 grams; during 3 minutes, 0.98 grams; and during the 5-minute interval 1.32 grams. The amounts during the longer intervals were not maintained strictly constant, because the experimenter stood ready to place additional small pellets in the food box if the rat finished the amount already placed there. This procedure was followed in order to insure that all of the time spent by the rat in the food box was taken up by eating. The food-weights here given were constant for the ½- and 1-minute interval, and did not vary more than 0.08 gram for the three longest intervals.

Each of the rats in the 5-minute-interval group was observed to be quite active and to eat food after the experiment had been completed. It is therefore held unlikely, but possible, that the amount of food (10.56 grams) consumed by the rats in this group during eight reinforced trials exerted a significant depressing influence on the strength of the hunger drive.

Results

Acquisition.—The average logarithm of the latent period for each trial of acquisition in the five groups of rats is given in Table 2, together with the average deviation of each value. The data are

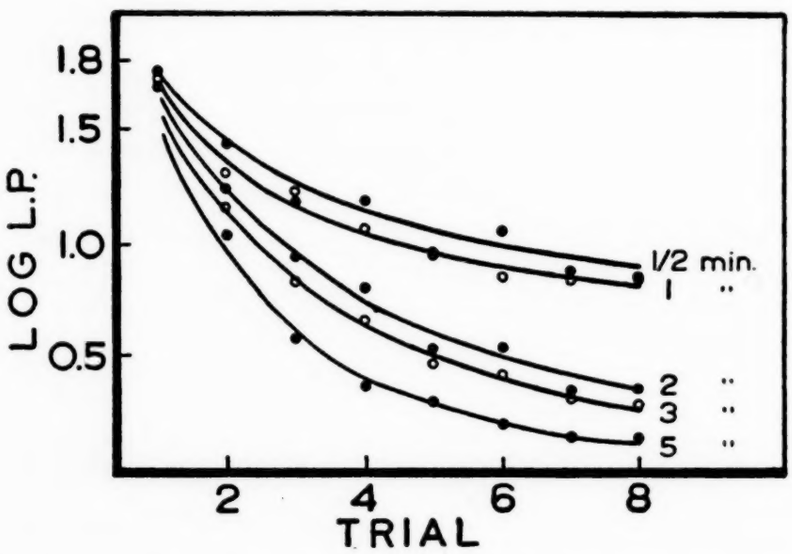

FIG. 3. The effect of spacing of trials on the course of acquisition, when the rat is allowed to eat throughout all but the final ten seconds of the interval between trials. The curves for the five groups are drawn by inspection through the experimental points. Each point represents an average of values obtained from 12 animals.

shown graphically in Fig. 3, which exhibits the relation between log latent period of the response and the number of trials of acquisition. In this figure, the acquisition curves are drawn by inspection as best-fitting lines through the experimental points. The five groups begin

acquisition with an average log latent period value of *ca.* 1.72 (53 seconds). They become more widely separated as acquisition proceeds. On the eighth trial, the ½-minute-interval group has an average log latent period of 0.83 (6.8 seconds); the 1-minute-interval group, 0.84 (6.9 seconds); the 2-minute-interval group, 0.36 (2.3 seconds); the 3-minute-interval group, 0.29 (2.0 seconds); and the 5-minute-interval group, 0.13 (1.4 seconds). Obviously the differences between the ½-minute and the 1-minute trial interval groups are not significant. However, on the fourth trial, the *t*-test indicates that the differences between the experimental values of any two non-

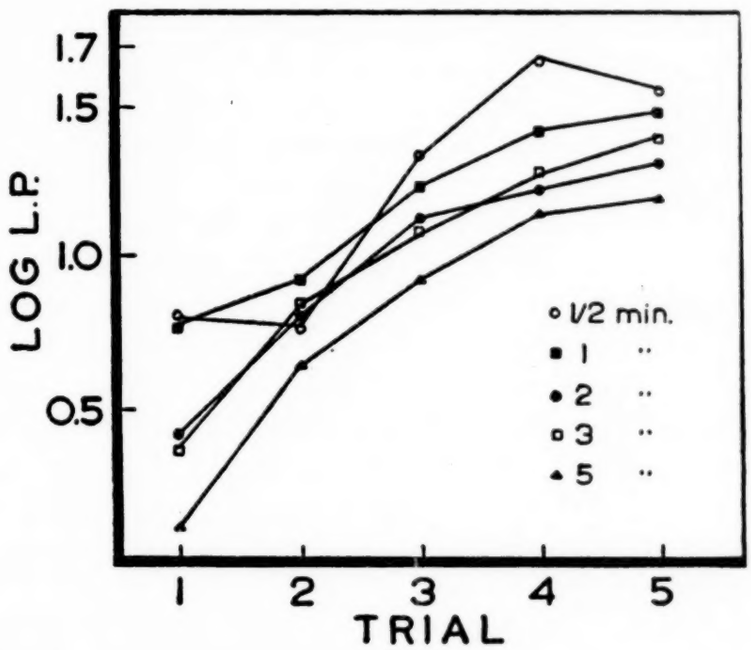

FIG. 4. The effect of spacing of trials on the course of extinction. The curve for each trial-interval group has been constructed by connecting experimental points. Each point represents an average of values obtained from 12 animals.

adjacent curves are highly significant ones, and could be expected to occur by chance with a probability of less than one percent.

According to these results, as the interval between successive trials is increased, the rate of acquisition of a conditioned operant response also increases, provided the reinforcement lasts throughout the interval between trials. The latter condition was fulfilled in our experiment by allowing the animal to eat during the entire time spent in the food box.

The results of this experiment are more similar to earlier findings than those of Experiment I. It will be recalled that Calvin (1) and Humphreys (6) found an increase in the rate of acquisition with an increase of interval between trials from 6.7 seconds up to 1 minute, in the conditioned eyelid response. The differences between this

to allow more time for inhibition to die away, and for spontaneous recovery to occur. Consequently these two factors work against each other in the determination of response strength. With the shorter intervals the first effect, that of decreasing effectiveness of reinforcement, is most marked, and is revealed as a decreasing rate of acquisition up to the 2-minute interval. Beyond this interval the stimulating effect of the unconditioned stimulus is reduced very slowly, according to our reasoning, and the second factor, that of increased spontaneous recovery, begins to show itself in the increased rate of acquisition. By this reasoning, rate of acquisition may be expected to pass through a minimum.

The results of Experiment II may be understood in a similar manner. Here an attempt has been made to keep the effective reinforcement at a constant high value by allowing the animal to eat throughout the interval spent in the food box. Under these conditions the effect of increasing the interval between trials is simply to maintain the 'stimulating effect' of the unconditioned stimulus constant, or nearly so, and to provide greater strength of response by allowing more time for inhibition to die away. This effect is revealed as an increased rate of acquisition and a higher asymptote for the curve with longer intervals between trials. Such a conclusion is justified by our experimental findings.

It is more difficult to indicate the implications of our ideas with regard to extinction. Experiments I and II show qualitatively the same type of result if due allowance be made for different final levels of acquisition. Both show the same disproportionately low value of latent period for the short-interval curves on the second trial, and the more typical smooth curves for the longer intervals. It is difficult to say whether or not the curves of Experiment I (constant food) have different asymptotic values, but certainly these are clearly shown by the curves of Experiment II. In line with our argument concerning acquisition, it might be pointed out that this is what we should expect if longer time intervals lead to greater spontaneous recovery. This would follow from the consideration that the final level of extinction is an equilibrium between spontaneous recovery and an inhibitory extinction effect, in which case the final response level for the total extinction process would be greater as the trial intervals (and hence the recovery process) increased.

A final word should be said about the course of extinction for 'massed' trials. The disproportionately low value of log latent period which appears in both experiments on the second extinction trial in those groups having trials spaced at $\frac{1}{2}$- and 1-minute intervals is a fact which serves to complicate an account of extinction. Hovland (5) has made a systematic study of a similar effect in the extinction

of the conditioned galvanic skin response. He finds the effect to be most clearly shown when preceding acquisition trials are massed, and it is significant that this same phenomenon occurs in the present experiment in a conditioned response of an entirely different type.

Summary

1. Two experiments were performed to determine the influence of spacing of trials on the rate of acquisition and extinction of a conditioned operant response. The conditioned response was the running of rats from a starting box on one end of an elevated runway, 3 feet in length, to a food box at the other end. The response was measured by the latent period, which is defined as the time required by the rat to leave the starting box, after the door is opened.

2. In a first experiment fifteen trials of acquisition and five of extinction were measured in six groups of eight rats each, with trials spaced at ½ minute, 1 minute, 2 minutes, 3 minutes, 5 minutes, and 10 minutes in the different groups. The unconditioned stimulus was a food pellet weighing about 0.06 gram, the size of which was kept constant for all the groups throughout the experiment. The results show a progressively decreasing rate of acquisition with increased interval between trials in the ½-, 1-, and 2-minute groups, and an increasing rate thereafter. In addition, the curves appear to be approaching different limits of log latent period, the asymptotic values increasing from the ½- to the 2-minute groups, and then decreasing again. The reliability of this trend is indicated by the existence of significant differences in latent period on the fifteenth trial, between the 2- and ½-minute groups, and between the 2- and 10-minute groups. The curves of extinction for the groups having trials spaced at ½-minute and 1-minute intervals exhibit significant depressions in rate on the second extinction trial. From this trial on, the extinction curves of these groups exhibit a faster rate than those of the longer-interval groups.

3. A second experiment was concerned with the measurement of latent period in eight trials of acquisition and five of extinction for five groups of twelve rats each. The trials for the respective groups were spaced at intervals of ½ minute, 1 minute, 2 minutes, 3 minutes, and 5 minutes. In this experiment, reinforcement was 'spread' throughout the interval between trials by allowing the rat to eat for the duration of the period spent in the food box. The data reveal that the rate of acquisition is increased, and the limiting value of log latent period is decreased, as the interval between successive trials is made longer. On the fourth trial of acquisition, significant differences are found between the points of any two non-adjacent curves.

Extinction curves again show a depression in rate on the second trial for the two shortest-interval groups. The curves of extinction appear to be approaching different limiting values of log latent period. As the interval between trials increases the limiting value for the extinction curve decreases.

4. The results are discussed in the light of some theoretical ideas regarding conditioning.

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CONVERTING A SPINAL *CR* INTO A REFLEX

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I. Introduction

Since the initial demonstration of spinal conditioning [*i.e.*, the acquisition of a new or learned response by an acute spinal preparation subjected to the conditioning technique] by the first author in the fall of 1936, several preliminary reports (**3**, **7–12**, **16**, **17**) dealing with various phases of the phenomenon have been made and two papers have been published [Shurrager and Culler (**14**, **15**)]. The first paper simply describes conditioning and extinction in the spinal dog, and the second is concerned with the conditioned extinction of a spinal reflex. Spinal conditioning and the extinction of an inherent reflex in the spinal animal are contra to the generally accepted theories (1) that spinal preparations are not able to acquire new responses, and (2) that spinal reflexes are inextinguishable except temporarily by fatigue [Sherrington (**6**)] or decrease in the excitability of the internuncial neurone [Prosser and Hunter (**5**)] and are in either case subject to spontaneous recovery and disinhibition.

In 1938 Shurrager and Culler (**13**) reported the release of complex unilateral reflexes in response to a stimulation of the paw in a spinal dog when all ventral roots contralateral to the side stimulated had been severed. The development (or release) of so-called 'unilateral progression reflexes'[2] (**17**) after sectioning of the contralateral ventral roots, together with the evidence of bilateral opposition in conditioned extinction, suggested that contralateral inhibitory mechanisms operate in the isolated spinal preparation.

In the present paper further evidence is cited in support of the theory that persistent inhibitory mechanisms operate in the spinal preparation in opposition to contralateral responses, reflex or conditioned. An experiment is reported in which a spinal conditioned response (*CR*) became so firmly established that it was impossible to extinguish it when all contralateral spinal roots posterior to the transection of the cord had been cut.

[1] Publication No. 2 in a series of experiments on neural and physiological bases of learning completed during tenure (1939–40) as National Research Council Fellow in Psychology at the Laboratory of Physiological Psychology (Animal Hearing Laboratory) transferred from the University of Illinois to the University of Rochester in September, 1938. This laboratory was maintained by aid of the Research Council, American Otological Society.

[2] In addition to the abstract (**17**), a paper is being prepared by Shurrager and Shurrager describing unilateral progression phenomena.

II. Procedure

The dogs, ranging in age from two months to three years, were operated under ether anesthesia. They were first cannulated and both semitendinosus muscles (S-T MM.) exposed. The entire lumbo-sacral section of the cord was then exposed, ligated in two places just anterior to the level at which the third lumbar roots emerge from the dura, and severed between the ligatures. The dorsal and ventral roots of the spinal nerves posterior to the transection were separated between the cord and a point near the dorsal root ganglion. Bands of rubber dam were looped around the individual roots, in order to facilitate locating and severing them during post-operative experimentation.

Each animal, after complete recovery from the anesthetic, was trained to respond with a flexion of one S-T M. to a slight shock to the tip of the tail. This spinal *CR* was established in the usual manner, elsewhere described in detail (**8, 14**), by administering two tail shocks (*CS*'s) of less than ten volts AC one second apart, and then one second later combining a third *CS* with a shock to the hind paw (*UCS*). Conditioning was continued until the criterion of ten correct responses in a unit of ten trials was attained. As a precaution in establishing the authenticity of the *CR*, it was extinguished to a criterion of ten successive failures to respond in a tens unit, and then reconditioned long enough to establish the response firmly. After this preliminary training, the experimental procedure was simply the progressive severing of various combinations of spinal roots in order to determine the minimum number of dorsal and ventral roots necessary for the maintenance of the previously established *CR*. Sectioning of the roots one at a time was alternated with checks of the *CR*. When the response was absent after severing a spinal root, it was reinstated before further root sectioning was done.

III. Results

Spinal preparations subjected to extensive transection of the spinal nerves often become non-functional before the critical part of the experiment is reached. Only five animals survived the alternate sectioning of spinal roots and conditioning trials to arrive at the final crucial test period when three spinal roots on the side stimulated remained intact, all contralateral roots were cut, and the *CR* became inextinguishable.

Loss of effective relationship between *CS* and *CR*, *UCS* and *UCR* in the spinal preparation often results from an inadquate blood supply to the spinal cord, possibly accompanied by operative shock. The fact that the spinal radicular arteries and veins anastamose enables some preparations to get a sufficient blood supply into the cord along the 7th lumbar nerve, one sacral dorsal root (2nd or 3rd), and the intradurally sectioned 3rd lumbar roots [3] to maintain it at a functional level after all other spinal roots and their accompanying blood vessels have been transected. Failure to demonstrate conditioning or the conversion of a *CR* into a reflex in the spinal preparation is invariably accompanied by hemorrhage under the dura, with simultaneous complete or almost complese loss of the *UCR* (inherent reflex).

[3] The radicular blood vessels of the right third lumbar roots are necessary in order that the delimited preparation remain functional. Suh and Alexander (**19**) and Bolton (**1**) described this radicular vessel in the human spinal cord, but did not ascribe any particular significance to it. Ligature just anterior to the third roots in the dog eliminates the anterior branch of the blood vessel and at the same time may ligate for section the third spinal roots intradurally, since they regularly proceed anteriorally under the dura from their point of entrance into it before entering the cord.

The S-T M. is innervated primarily by the 6th and 7th lumbar and 1st sacral ventral roots. The presence of these roots on the side contralateral to the *CR* was found to be highly significant in the present experiment.

The five dogs of Table I were successfully carried through the following post-operative procedures: (1) the *CR* (a fleck of the insertional end of the S-T M.) was established to a criterion of ten

TABLE I

RECORDS OF SPINAL PREPARATIONS IN WHICH A *CR* OF THE S-T M. BECAME INEXTINGUISHABLE

Dog	1 *C*	2 *E*	3 *reC*	4 *C*	5 *C*	5 *C*	7 *C*	8 *C*	9 *reE*
1	40	50	25	17	11	2	0	0	205
2	50	40	27	16	8	2	0	0	306
3	40	40	28	19	12	0	0	0	479
4	60	50	29	23	13	1	0	0	720
5	30	30	15	11	16	1	0	0	126
Av.	44	42	24.8	17.2	12	1.2	0	0	367

Conditioning (*C*), extinction (*E*), reconditioning (*reC*), and reëxtinction (*reE*) trials imposed upon isolated lumbo-sacral spinal preparations which were subjected to various post operative procedures fully described in the text. *C*'s of Columns 4, 5, 6, 7, and 8 are post operative reenforced trials used to reëstablish the *CR* when it failed after a root was severed. If the *CR* was present to the first *CS* after sectioning a root, the *CS* was not reinforced and the trials is not recorded in the table. (1) Initial *C* trials; (2) Trials necessary for *E*; (3) *ReC* trials required to insure a good *CR* before going on to the critical part of the experiment; (4) *C* trials used to maintain the *CR* during severing of 16 ipsilateral dorsal and ventral roots; (5) *C* trials necessary to maintain the *CR* during severing of 10 contralateral dorsal roots; (6) *C* trials necessary to maintain the *CR* during the severing of 8 non-critical ventral roots; (7) *C* trials necessary after sectioning the 6th contralateral lumbar ventral root; (8) *C* trials necessary after sectioning the 7th contralateral lumbar ventral root; (9) *ReE* trials which failed to extinguish or even diminish the size of the *CR* after all contralateral roots were cut.

correct responses in a tens unit; (2) The *CR* was then extinguished to a criterion of ten successive failures to respond to the *CS* in a tens unit; (3) Reconditioning was carried on till the *CR* was once more firmly established; (4) The spinal nerves on the ipsilateral (conditioned) side were severed root by root at the distance of the sensory ganglion from the cord until only two dorsal roots, 7th lumbar and 2nd or 3rd sacral, and one ventral root, 7th lumbar, remained intact. (The *CR* was occasionally not present at the first presentation of the *CS* after a root had been cut, but it was always easily reëstablished by one or more conditioning trials. See Table I, Columns 4, 5, 6, 7, 8.); (5) All contralateral sacral and lumbar dorsal roots were cut one by one with intervening tests of conditioning; (6) The contralateral sacral and lumbar ventral roots were cut one by one until only the 6th and 7th lumbar remained intact without effecting any

observable change in the nature of the *CR*; (7) The contralateral 6th lumbar ventral root was severed (this produced a slight increase in the magnitude of the *CR*. In two preparations (Dogs 3 and 4, Table I) the increase was quite obvious); (8) The last remaining contralateral root, 7th lumbar ventral, was severed (this was followed by a marked increase in the magnitude of the *CR*, which now appeared to involve the whole S-T M. in a reflex twitch); (9) The *CS* was presented alone for from 126 to 720 trials at 10- to 60-second intervals without causing failure of the *CR* or diminution of its size.

The great number of unreinforced trials which failed to bring about extinction of the *CR* after all contralateral roots were severed seems to warrant the conclusion that it had become as inextinguishable as a reflex. However, the converted *CR* still retained two characteristics of conditioned responses which distinguish them from reflexes. First, the response did not summate to sustained or rapidly repeated stimuli; and second, a weak stimulus to the tip of the tail evoked as full a contraction as a strong stimulus. Reflexes summate to sustained stimulation, and the size of an inherent reflex response is directly affected by the intensity of the stimulus which elicits it.

The method of surgical delimitation here used makes strikingly apparent that the mechanisms mediating the converted *CR* must be located within a very circumscribed section of central nervous tissue posterior to the 3rd lumbar roots. It was even possible to lift the segment of cord below the transection completely out of its bed in the vertebral column, leaving it attached to the animal only by the three roots ipsilateral to the response. However, when spinal roots are severed it is impossible to demonstrate, in the manner that makes the conditioning techniques so valuable to neural research, the alternate presence and absence of a given response as conditions are varied. If, instead of sectioning of the nerves, a neural block [*i.e.*, quick freezing or local anesthesia] method could be employed, it might be possible to study more exactly the facilitory or inhibitory effect of the presence of the various roots in the preparation, since the nerves could be rendered alternately functional and non-functional and the effect upon the *CR* noted. But the drastic changes in the *CR* when the last contralateral ventral roots are severed is a most convincing demonstration of their inhibitory effect, when intact, upon the *CR*.

IV. Discussion

The data presented in Table I demonstrated that in five spinal animals a *CR* of the S-T M. to tail shock was established and maintained after the spinal cord had been transected just above the level at which the 3rd lumbar roots emerge from the dura and all roots

posterior to the transection severed with the exception of the ipsilateral 2nd or 3rd sacral dorsal and 7th lumbar dorsal and ventral, and contralateral 6th and 7th lumbar ventral. As the two contralateral roots were severed one after the other, the *CR* progressively assumed the character of a spinal reflex, in that it was impossible to extinguish it, although in one case the experimental extinction was continued, with occasional interruptions, through 720 trials (Table I, Column 9).

A question may be raised as to whether the *CR* which became reflex in its inextinguishability after the proper contralateral roots were severed might not have appeared spontaneously as a reflex after the sectioning of those roots *without any previous conditioning*, just as unilateral progression reflexes appeared in spinal preparations when all contralateral ventral roots were cut. It seems highly improbable that this would have happened [*i.e.*, that the S-T response to tail shock would have appeared spontaneously as an inherent reflex released from inhibition when certain contralateral roots were cut], since the converted *CR*, although it became inextinguishable, still retained two striking properties of spinal *CR*'s which distinguish them from reflexes. It did not summate to repeated or sustained stimuli, such as AC shock or repetitions of AC shock at intervals under a second, and a minimal *CS* continued to elicit a maximal *CR*. That the converted *CR* retained the properties of non-summation and, as far as could be observed, all-or-none response to a liminal *CS*, in the final evaluation of spinal conditioning data, may come to be regarded as significant.

It has been previously shown that reëxtinction, as well as reconditioning, in the spinal preparation with intact spinal roots proceeds more rapidly with each repetition of the processes (**7**, **8**, **14**, **16**). The large number of trials of attempted extinction recorded in Column 9 of Table I, when compared with the number of trials required for complete extinction in Column 2, leaves no doubt as to the changed nature of the spinal *CR* after sectioning of the contralateral ventral roots.

A second change in the spinal *CR* which appeared as the 6th and 7th contralateral ventral roots were severed was the progressive involvement of the whole S-T M. in the response. Prior to sectioning of the specified roots the response had been confined to a small group of muscle fibers near the insertional end of the muscle. As the contralateral roots were cut, there was a spontaneous increase in the number of responding muscle fiber groups in the *CR*.

The spontaneous increase in the magnitude of the *CR* when contralateral inhibition was removed is additional evidence in support of the previously postulated theory that conditioning cumulates

subliminally at the individually conditioned synapses. The sudden increment in response when contralateral roots were cut seems to indicate that the balance of the muscle had been subliminally conditioned and that this central conditioning could only become peripherally effective when released from contralateral inhibition.

The apparent release of inhibition by severing the contralateral motor roots is completely in accord with the results of two previous studies reported with the collaboration of E. A. Culler. Those studies, one dealing with complex unilateral reflexes (**13**) and the other with the conditioned extinction of a spinal reflex (**15**), had already suggested effective contralateral inhibitory mechanisms in the spinal animal. The evidence pointing to such a conclusion is briefly reviewed below.

The complex unilateral reflexes described in the first paper were observed to occur when the spinal cord was ligated and cut above the third lumbar spinal roots and all nerves on the side stimulated transected except the 6th dorsal and 7th ventral roots. The stimulus applied to the paw (a short flick of a contact switch) was maintained at an intensity of 300–400 volts AC. As the contralateral motor roots were progressively severed, 'unilateral progression' (**9**) developed from the original flexion-relaxation of the simple spinal reflex to the flexion-relaxation-extension-relaxation pattern which, when all contralateral roots had been cut, often repeated itself as many as three times in a relatively slow and precise sequence. All contralateral sensory roots could be cut without releasing complex reflexes on the side stimulated. The development of unilateral progression was directly dependent upon the elimination of contralateral ventral roots.

The second paper referred to described the progressive conditioned extinction of a spinal reflex in a preparation with all roots posterior to the transection of the cord intact. An inherent reflex of one S-T M. to tail shock was effectively and permanently inhibited by conditioning the corresponding muscle of the opposite leg (in which no inherent reflex to tail shock had been present) to flex to the same stimulus. As the *CR* became more firmly established the reflex failed.[4]

Although conditioned extinction lends greater plausibility to the theory that an active contralateral inhibitory mechanism exerts a cumulative and persistent effect upon reflex action in the spinal animal, there is no evidence that the inhibitive mechanisms of conditioned extinction are identical with or even similar to those overcome by severing the contralateral roots in this or the unilateral

[4] This is consistent with the statement of Creed, *et al.* (**2**) to the effect that the inhibitory effect of an interfering activity is a function of its intensity [*cf.* Hilgard and Marquis (**4**, 108 ff.)].

progression experiment. The inhibition in conditioned extinction can only be ascribed to a cumulative function somehow dependent upon contralateral activity and similar to the cumulative functions of conditioning and extinction and central conditioning and central extinction described earlier (**7, 8, 14, 16**). Both dorsal and ventral roots were intact when conditioned extinction was demonstrated and it was apparently brought about through the active competitive bilateral functioning of sensory and motor components of the isolated preparation. Therefore, in conditioned extinction no definite localization of the contralateral inhibitory mechanism is possible.

The occurrence of unilateral progression and of conditioned extinction in the spinal dog, together with the evidence of the conversion of a spinal *CR* into a reflex presented in this paper, suggest three general hypotheses applicable to spinal reflex phenomena:

(1) Extinction of a *CR* in the spinal preparation depends upon the existence intact of the ventral roots contralateral to the response to be extinguished. (In the normal animal extinction probably depends upon contralateral inhibition mediated by the cortical analogue of the spinal ventral roots.[5]);

(2) Inhibition of inherent reflexes at the spinal level depends upon contralateral inhibitory mechanisms of the ventral roots. At the higher brain levels inhibition probably depends upon the analogues of the spinal ventral roots;

(3) So-called inherent reflexes of the complex type develop by a process analagous to conditioning prior to the establishment of effective contralateral inhibitory mechanisms. They are then, because of their priority, superior to contralateral inhibition, except as it is appropriately supplemented in a technique such as conditioned extinction.

V. Summary

Further evidence is presented in support of the previously postulated theory that persistent contralateral inhibitory mechanisms operate in the spinal dog. Records are presented from five dogs in which a spinal *CR* of the insertional end of the S-T M. to tail shock came to involve the whole S-T M. and assumed the reflex property of inestinguishability when all contralateral ventral roots posterior to the spinal transection had been severed. The conversion of the spinal *CR* into a reflex is interpreted as resulting from the removal of an

[5] A paper is in preparation which demonstrates that complete removal of the ipsilateral electrically excitable cortex (Brodman's Area 4) [Smith (18)] specific for a response contralateral to the *CR* renders that *CR* directly inextinguishable.

inhibitory influence exerted upon the response mechanisms via the contralateral ventral roots.

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WORK METHODS AND LEARNING

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In a recent survey of experiments on fine motor skills (**6**) Seashore has shown that the individual differences found are large and fairly stable, and that their origin is not adequately explained in terms of constitutional factors such as body build and physiological limits. Neither are they adequately explained by differing amounts of direct or transferred training. Since the group factors of motor abilities so far discovered cut across the lines of specific sensory fields and musculatures employed, and tend to follow, instead, similarities in *patterns of behavior*, Seashore has postulated the possible importance of *work methods* as a basis for these individual differences in fine skills of all sorts, and has reviewed the evidence for this neglected aspect of psychology (**7**).

The present study attempts to test this hypothesis of the importance of work methods in individual differences by a detailed analysis of a relatively simple motor skill, namely card sorting. This test offered a number of advantages: (*a*) it is representative of many common skills that employ both hands, (*b*) it involves only simple apparatus and materials, (*c*) it permits a wide variation in movements employed, (*d*) it can be timed and recorded with slow motion pictures, and (*e*) the Husband-Miles procedure (**4**) of sorting according to the preceding card is unfamiliar to most subjects and therefore illustrates earlier as well as later stages of learning.

Specifically, our experiment investigates (*a*) the extent to which individual differences in this manual skill may be related to variations in work methods employed, and (*b*) the extent to which an individual's improvement in skill through learning is related to these same work methods. In both cases we have attempted to go beyond the mere measurement of skills by determining the qualitative factors which underlie these quantitative variations.

Historically, Bryan and Harter (**2**) have shown the inadequacy of explaining individual differences in motor skills in terms of biological capacity. Even if there is a physiological limit for a given work method, some other work method may prove more efficient for the performance of the same task, and overcome the limitations. Book (**1**) found similar evidence of this in his experiments on typing.

* The research was conducted in the psychological laboratory of Northwestern University during 1940.

In industrial engineering, the necessity for overcoming individual limitations in manual skills has commonly been met by substituting machines for human beings in difficult or routine performances. Where this has not been done, consulting engineers specializing in time and motion study have frequently been called in to compare the work methods of the best and poorest workers and to set up optimal work methods for all workers. The Gilbreths (**3**), who pioneered in such motion studies, have been able to analyze all common manual skills into eighteen descriptive units called 'therbligs,' *e.g.* 'grasp,' 'transport loaded,' 'release,' 'transport empty,' etc.

This type of analysis is now a fairly common type of consulting engineering service and the slow motion picture techniques and materials have themselves been quite well standardized. Unfortunately for psychology relatively few such studies are published because the results are often valuable trade secrets. Psychologists themselves have neglected this fairly well known method of motion study in their analysis of human abilities, both as variations between different individuals and within the same individual during learning. The method, although subject to some limitations, is equally applicable to both occupational and avocational skills.

Procedure

An ordinary deck of 52 playing cards was sorted into a four-sectioned wooden box placed on a small table. Each of the $5\frac{1}{2} \times 8$ inch sections was clearly labeled with the symbols of one of the four playing suits.

The following instructions were given to each subject as he or she stood before the table: "Hold the deck in your left hand with the reverse side up. Throw the first card in the upper left-hand corner box, face up, regardless of its suit. Sort each succeeding card on the basis of the previously thrown card. Each card is thrown into the box whose symbol is that of the card just previously thrown. (Here the subject sorted a few cards with supervision.) If you make an error, proceed from that point as if you had not made the error. Two seconds will be added to your time for each error; you would use much more time if you stopped to correct it yourself. Your score is the time required for sorting the complete deck of cards. After each trial please report anything which you think has influenced your performance, any changes in method which you might have noticed and if you remember them, the number of errors you made. We are interested in finding out what changes occur during learning and any suggestions will be valuable."

The deck was held in the left hand by all subjects, regardless of hand preferred. The trial score was the time required for sorting the complete deck of cards, clocking the moment that the first and last cards hit the box.

On the basis of an informal preliminary investigation using about thirty Northwestern University undergraduates, both male and female, a separate check list for each hand was constructed in order to record the observable behavior patterns used in card sorting. A short questionnaire included items on personal data, handedness, familiarity with cards, and a crude anatomical classification of hands and fingers, together with space for the experimenter to record the introspective report of the subject after each trial was used.

Twenty-two Northwestern University women students served as subjects for the basic analysis. They were all advanced students of a laboratory course in systematic experimental psychology. Each subject was given a series of twenty trials in a single testing period. The exploratory endeavors of the experimenter led to slight variations in the interval between trials as well as the activities of the various individuals during the short interval. The time scores and the introspective reports concerning conscious changes in work methods or any other in-

formation which the subjects volunteered were recorded after each trial. During the trial the experimenter marked the check list of the right hand behavioral patterns while a student assistant checked the fewer movements of the left hand.

The performance of an additional female subject was recorded in motion pictures while learning the task. As with all other subjects, this student was given twenty trials. Parts of certain trials were photographed throughout the series. An electric stop-clock reading to one one-hundredth of a second was placed on the table so as to be included in the picture. The samples serve as a basis for a therblig analysis of the behavioral units at different stages of learning for a given individual. Camera speeds were varied in order to determine what speed was most adapted to this type of work.

Micro-motion studies were made on samples of the first trials of one male novice and of one well-practiced male subject whose average time score was equivalent to that of the last trials of the above mentioned female subject. This permits not only of a comparison between individuals at equivalent stages of practice but also comparison between individuals at equivalent stages of performance.

Data and Interpretation

Individual learning curves were plotted for each subject. It was found that except for the very earliest trials errors are negligible and for that reason they were disregarded in the time scores altogether. It is fairly easy for the subject to report the number of errors made on each trial—these were recorded. It is apparent that the poorer time scores are related to the trials with many errors. Naturally there are marked differences between the individual curves and irregularities within each. Only a qualitative examination of the observations, introspective reports of the subjects, and the effect of conditions prevailing during the intervals between trials will be presented here.

A work method or behavior pattern is a way of reacting to a given situation. This includes, as Seashore (7) points out, set, attitude, approach, trick of the trade, etc., and here we are concerned with the qualitative variations in methods. Some of the patterns checked were suggested by Perrin's (5) early work. Most individuals varied their work methods from one trial to another and even within a single trial.

One of the most common patterns noticed was the use of a high degree of verbalization, not necessarily audible, in the early trials. The symbol of the card falling into the box was verbalized and seemed to serve as the stimulus for the response of directing the next card into the proper box. All individuals showed appreciable reduction of this factor, and some had apparently discarded it entirely by the last trials. The best sorters seemed to use a minimum of verbalization. Of this latter group some evidenced no verbalization throughout the twenty trials, and those who used the method discarded it early. There was ample evidence from the reports of the subjects and from observation that symbolic processes other than verbalization were used by many individuals. In two cases showing no ver-

balization eye movements appeared to be kinæsthetic cues for the direction of hand movements.

A smooth rhythmical process usually appeared to be more efficient in the matter of energy cost, and was a characteristic of the fastest sorters. Many subjects who exhibited no such rhythmic quality at first developed it by the end of the series. Rhythm seems to be achieved by an overlapping of the component behavior units of therbligs. Several subjects reported a facilitating effect of the rhythmical sound of the cards and were disturbed by its absence when some blocking occurred.

A mistake in a trial often led to confusion and frustration which naturally slowed the trial. Many observers showed definite improvement in their attitude toward mistakes realizing that hypertension made for even more errors. Excitement brought about random movements which were larger and more forceful than would be economical of time and energy. Practically every subject reported that she performed and felt better when she did not concentrate too much on the process.

No specific directions for turning the card with the right hand were given. Some students retained the same method throughout but many of them changed. It was quite apparent that any method which made it very easy for the subject to see the face of the card in his right hand led to confusion, blocking and indecision. This undoubtedly was a perceptual factor. It should be pointed out here that the sorting probably was most efficient when the eyes were directed to the card which had just fallen into the box, since the direction of the succeeding card was determined by it and not the suit of the card in the hand. Thus, when the card in the hand was effective as a stimulus, it was not unreasonable to expect that this stimulus aroused its own response which interfered with the cue to the correct response. Several subjects unknowingly were confused by this item for the first ten trials. When instruction as to the nature of their difficulty was given, their time scores improved immediately. Other subjects discovered the difficulty themselves and changed their methods accordingly. Therefore, for this skill it was a 'trick of the trade' to handle the cards for the least perceptual confusion. Most of the subjects began by first looking at the card in the hand, then to the box, but the trick of focusing vision on the box was usually acquired early.

One interesting observation was the definite advantage of self instruction to the subject. Here, during the rest interval, the subject was instructed to decide what things seemed to facilitate the sorting task and what things inhibited it. After this self-analysis a plan of attack on the next series of trials was formulated verbally.

One subject formulated this typical plan: "Relax, don't concentrate too hard, hesitate long enough at error to prevent getting excited, keep a rhythm."

The average times per trial for the entire group began at 83.7 seconds for the first trial, dropped rapidly to 51 seconds for the tenth trial and then tapered off more gradually to 45.8 seconds for the twentieth trial.

To note the difference in behavioral patterns which might be characteristic of the better or poorer card sorters, the five best and the five poorest records on the last three trials were compared.

Observable changes in methods occurred mostly during the early trials of the series. Three minor trends were discovered: (1) in grasping the card from the deck hand, the lower five subjects all placed the right thumb on top of the card while two of the upper five placed the thumb on the bottom; (2) each of the best group used only the thumb and first two fingers of the right hand in handling the card but the poorest group used three of four fingers to assist the thumb; and (3) a definite rhythmical pattern was noted in the last trials of the best group while two of the worst group still exhibited no rhythm at the end of the series.

The analysis of the questionnaire items revealed no differences between the upper and lower groups in handedness, habits of handling the deck, or in the crude anatomical classifications of shape and size of hand and fingers. There was however a marked discrepancy between the groups in the familiarity with cards. Only two of the lower five indicated that they had played bridge or other card games at all and one of these had started within the year. Of the remaining three, one expressed a definite dislike for cards as long as she could recall, one had played very little, and the other indicated that she had never played cards. Three of the upper group played several times a week and the remaining two indicated that they played cards as frequently as once a week, which suggests at least a moderate degree of positive transfer from regular card games to this new test.

An attempt was made to discover any characteristic changes in work methods occurring between the early and late trials of the learning process. For this, the behavioral patterns of the first and last five trials were compared for the best and poorest five sorters used above. The better group tended to develop a characteristic rhythmical pattern from the first trials to the last while the poorer performers did not, to any marked extent. Rhythm may not be a unique work method, but rather a characteristic temporal combination of the behavioral elements included in a method, but it seems a necessary characteristic of good performance.

The inadequacies of the questionnaire diagnosis of finer changes of work methods within and between trials of any given individual while perfecting a motor task, led to the use of micro-motion study techniques involving a frame-by-frame analysis of a high speed motion picture film of the process. The film analysis here reported has

TABLE I

INDIVIDUAL THERBLIG ANALYSIS *
Female Subject N. C.

Trial	Score, Seconds	Camera Speed	Grasp	Transport Loaded	Release	Transport Empty
3	44.0	64	12	39	3	23
			20	57	6	29
			Averages 14.6	46.0	4.0	27.2
4	41.5	16	6	28	5	27
			15	32	12	30
			Averages 11.3	30.0	8.3	29.0
6	42.0	64	5	24	5	25
			29	42	10	35
			Averages 11.6	32.0	7.2	33.6
8	40.0	16	6	18	8	20
			20	40	20	40
			Averages 10.4	24.5	13.2	30.5
9	41.5	64	15	31	7	25
			52	49	15	31
			Averages 26.0	38.0	10.3	28.4
18	39.5	16	6	25	7	25
			15	70	12	39
			Averages 8.6	42.7	9.7	32.2
20	40.0	64	10	24	4	23
			19	38	13	36
			Averages 13.5	29.7	7.7	28.5

* Individual therbligs reported in one-hundredths of a second. The three figures for each therblig represent respectively the lowest, highest, and average time in hundredths of a second in dealing from three to five cards.

been limited to a time analysis of the individual therbligs involved in the motion of the right hand, namely 'grasp,' 'transport loaded,' 'release,' and 'transport empty.' Table I presents the analysis of the component movements for sorting from three to five successive cards in each of seven selected trials in the learning series for one individual. Unfortunately from the standpoint of analyzing quali-

tative changes in learning, this student's time score on her first trials was equivalent to the average performance of other subjects on the twentieth trial and showed no appreciable improvement during the twenty trials. One interesting result which came out of this analysis, however, was the localization of much of the wasted time. There were quite wide variations in the time for 'transport loaded' and some

TABLE II

INDIVIDUAL DIFFERENCES BASED ON THERBLIG ANALYSIS *

A. Equivalent Stages of Practice

Subject	Trial	Score, Seconds	Camera Speed	Grasp	Transport Loaded	Release	Transport Empty
M.P.....	1	67	16	6	38	3	33
				14	48	6	40
				Averages 11.4	44.2	4.0	36.2
N.C.....	3	44	64	12	39	3	23
				20	57	6	29
				Averages 14.6	46.0	4.0	27.2

B. Equivalent Stages of Perfection

N.C.....	20	40	64	10	24	4	23
				19	38	13	36
				Averages 13.5	29.7	7.7	28.5
V.D.....		41	16	6	9	12	18
				9	32	32	29
				Averages 7.4	22.2	21.5	23.5
R.S.....		50.5	16	5	46	6	21
				8	116	14	32
				Averages 6.2	69.2	8.2	26.8

* Individual therbligs reported in one-hundredths of a second. The three figures for each therblig represent respectively the lowest, highest and average times in hundredths of a second in dealing with from three to five cards. Averages of four or five cards sorted are not necessarily representative of the time for the whole deck.

remarkably high values. This was probably due to the discriminative feature of the task rather than to any purely muscular factor. The 'deliberation' motions, such as waving the right hand in the air while the proper decision is being made, are evidence of this interpretation.

The differences between individuals, at approximately equivalent stages of practice, in work methods used in performing the same task were quite apparent in the micro-motion study of the early trials of two novices. A male subject, M. P., completed his first trial in 67

seconds. A sample of this trial is analyzed and the figures presented in Table II above those for the third trial of subject N. C.—the first of her trials photographed.

It will be noticed in Table II that there was a difference in the time score of 23 seconds between the two subjects compared at nearly equivalent stages of practice. There seemed to be little difference in the time required for the therbligs with the exception of 'transport empty.' The difference between the averages of this therblig is 0.09 seconds in favor of the female and faster subject. Although the evidence was far from conclusive it was conceivable that a difference of this much in the time of a single therblig may have accounted for the individual differences. Individual differences may result from either significant differences between any one given therblig or combination of therbligs. This became apparent in a study of the individual differences at an equivalent stage of perfection as shown in Section B of Table II where the cumulative effect of the differences which occur between the individual therbligs, some of which were in favor of one subject, some in favor of the other, cancelled any significant difference for the combined process.

An analysis of a sample from a trial by another male subject, R. S., shows further differences. The two long values under 'transport loaded,' 1.16 and 0.76 seconds, came as a result of his turning the face of the card up in such a position that confusion with the card just thrown was possible. This was excellent quantitative verification of this blocking difficulty discussed earlier. It was further evidence, also, of the importance of the perceptual discrimination involved in the task. When the work method was changed so that the subject could not see the face of the card, this therblig immediately reduced to 0.46 seconds.

There may be slight inconsistencies in the degree of accuracy found in the analysis of trials due to the variations in the speed of the camera. The highest speed, or 64 frames per second, is by far the most accurate for this type of work.

The writer does not intend to imply that the shape of the learning curve for a complex motor skill, such as the one discussed, was the result of the gradual reduction to the physiological limit of each therblig involved in the work method originally employed. Although no quantitative data are here presented it was quite apparent in the film that *overlapping* of elemental components occurred, which had the net effect of reducing the time score even when there was no appreciable reduction in the given therblig. For instance, the film showed in the practiced subjects the 'pre-position' therblig of the left thumb, the motion of getting the next card in an accessible position, occurring while the 'transport empty' therblig occurs in the right

hand. Simultaneous motion charts of the activities of both hands should be constructed for representative stages of learning in order to bring out differences in work methods.

A definite limitation of the engineer's method of therblig analysis was discovered. A good part of the so-called wasted time is due to the psychological process of discrimination and *verification*, which cannot be adequately approached by therblig analysis technique. Reference to Table II indicates that the therblig during which verification occurred may vary from one individual to another. Compare N. C. and V. D. The latter required only 7.4 hundredths of a second in grasping, but 21.5 hundredths of a second, a much greater time, was involved in release. Introspectively it seems possible that one may release the card before being sure of the correctness of the response and it is conceivable that verification takes place before starting 'transport empty.' N. C., on the other hand, spent little time in release and much in grasping, the two processes requiring 7.7 and 13.5 hundredths of a second respectively. It may have been that she verified her next response while completing the grasp. Reduction in trial scores was apprently due in part to decrease in verification time which came with increased confidence in initial judgment.

It was early recognized that this particular task involved, besides skilled motor manipulation, a significant degree of perceptual ability. That is, the symbols must be discriminated correctly and a specific response made in placing the cards in the proper boxes. One response furnishes the stimulus which will direct the succeeding response. To test the assumption that some of the individual differences found may be due to discriminatory ability, the ten subjects upon whom the upper and lower quarter analysis was made were given additional tests. Two of Seashore's other tests were administered: (*a*) speed of simple discriminatory reaction, in which the right hand presses its respective key in response to the right of two lights, while the left hand in turn responds with the left key to the left of the two lights; (*b*) the serial discrimeter, in which the subject presses one of four fingers on keys corresponding to visual number signals (**9**).

Instructions as given by Seashore (**8**) were followed. For the simple discrimination a practice series of 25 trials preceded two regular series of 50 trials each. A one-minute practice on the serial discrimeter preceded two regular series of 5 trials each. The order in which the battery was administered was: practice trials on the simple-discrimination; first series of 50 trials on simple discrimination; practice on serial discrimeter; first series of 5 trials on serial discrimeter; second series of 50 trials on simple discrimination, second series of 5 trials on serial discirmeter.

Results are presented in table below:

TABLE III

DISCRIMINATION ANALYSIS

Subject	Sorting Score, Seconds	Rank	Serial Discrimeter Score	Rank	Discrim. Reaction Time, Seconds	Rank	Quarter
C.J.....	36.9	1	118.5	3	.267	2	
L.R.....	37.0	2	136.8	1	.225	1	
S.D.....	37.8	3	115.0	5	.297	5	Upper
N.Y.....	40.3	4	118.3	4	.270	3	
E.I.....	41.3	5	111.0	6	.273	4	
M.P.....	51.2	6	104.7	7	.317	9	
J.H.....	52.6	7	99.7	8	.314	8	
L.B.....	53.3	8	132.6	2	.301	6	Lower
M.H.....	54.3	9	91.9	10	.376	10	
C.K.....	55.0	10	96.5	9	.304	7	

It was apparent that the five best card sorters had significantly better discriminatory reaction times than the poorer card sorters. With the exception of one pair of reversals, the better group were also considerably better in the serial discrimination task. This relationship is being reinvestigated on a larger number of subjects.

SUMMARY

The significance of work methods in learning the complex motor skills of card sorting has been investigated by employing the techniques of photographic motion study, direct observation, and the direct introspective reports made by the subjects.

A qualitative analysis has indicated that the trial-to-trial fluctuations of a given individual and the relatively consistent improvement through training may be accompanied by changes from one work method to another and by perfection of a given method. The changes may be made to methods of more, less, or equivalent efficiency. Perfection may be accomplished by such things as variations in directive cues, elimination of distractive cues and the attendant motor interference, overlapping of the component processes and the establishment of a definite rhythm. The early rapid improvements in the learning curve seemed to be accompanied by the greatest number of gross changes in work methods, while later more gradual improvements were probably due largely to cue reduction and to overlapping.

Comparison of skilled and unskilled sorters from the upper and lower quartes revealed that the former group had the advantage of a direct transfer effect from previous card playing. Transfer may have been either of discriminatory habits of identifying suits or

manual manipulatory habits of sorting or both. Rhythmical patterns characterized the better group. Best sorters were further identified by superior speed in perceptual discriminations as measured by additional discriminatory tasks.

Upon examination of the quantitative variations between individuals in this learning process, qualitatively different patterns were found to be used in the execution of the task both at equivalent stages of practice and at equivalent stages of performance.

Much can be learned through controlled observation, but slow motion picture analyses are essential for more accurate investigation of both the grosser and finer changes in the development of a motor skill. Such a technique should be used to follow a number of subjects throughout an extended series, through all stages of learning.

For further investigation of motor aspects of skills, care should be exhibited in the selection of a task which involves a minimum of perceptual discrimination and the equating of subjects in discriminatory capacity.

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ELECTROENCEPHALOGRAPHIC INDIVIDUAL DIFFERENCES AND THEIR CONSTANCY: II. DURING WAKING[1, 2]

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In a preceding paper it was demonstrated that electroencephalographic individual differences may, under certain conditions, regress to a homogeneous level, and consequently, that a high degree of constancy or individuality of pattern may not always be maintained. These conditions were natural sleep and the resting state after awakening from all-night sleep. It was hypothesized that this reduction in electroencephalographic individual differences was correlated with a concomittant reduction of behavioral differences. From such an hypothesis one would predict that this lack of differentiation between subjects (or between groups of similar subjects) would tend to occur over a range of activities and not merely for the 'basal' (sleeping) and 'standard' (resting) conditions. The present report presents a preliminary attempt to verify experimentally this hypothesis.

Subjects and Procedure

From each of the four groups studied in the previously reported sleep experiments, one subject was selected for more extensive study during the waking condition. These four subjects may be regarded as constituting a small sample of the range of alpha indices found in the population at large, each subject falling into one of the four quarters of the percent time alpha scale suggested by Davis and Davis (2).

The amplifiers and recording apparatus used have been described in the first paper. Each subject was recorded at approximately the same time of day on five consecutive days, going through the following series of activities in alternating regular and reversed order where possible:

1. Resting condition A: *eyes closed, light off*
2. Resting condition B: *eyes closed, light on*
3. Resting condition C: *eyes open, light on*
4. Silent reading: *eyes open, light on*
5. Oral reading: *eyes open, light on*
6. Talking: *eyes open, light on*
7. Rotational addition: *eyes open, light on*
8. Rotational addition: *eyes closed, light off*
9. Resting condition D: *eyes closed, light off*

[1] The main content of the second part of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, in the Department of Psychology in the Graduate College of the State University of Iowa. August, 1940.

[2] This study is one in a series dealing with the electroencephalographic correlates of psychological process, under the direction of Dr. John R. Knott in the laboratories of the Department of Psychology in the State University of Iowa.

[3] The author wishes to acknowledge his indebtedness to Dr. John R. Knott, who directed this research.

Resting conditions A and D were presumed to be the usual 'standard' condition of eyes closed, mind at ease, body relaxed, and subject wide awake.

The reading material was an article on the training of pilots at the government air bases, taken from a popular magazine.

The talking condition involved simple summarizing of the material read, it being emphasized to the subjects that they were not being tested or scored on the material recalled.

In rotational addition, a number from one to ten was presented orally by the experimenter, to which the subject was instructed to add, consecutively, four, five, six and seven, and then repeat, until the cumulative total was called for. Each subject received the same problems on any given day. Each condition lasted from two-and-a-half to three minutes.

This procedure was used in an attempt to satisfy the proposition that a wide range of subjects and experimental conditions should permit the appearance of important or crucial changes in the EEG which may be related to individual differences in the EEG recorded under some standard condition.

Electrode placements for the different days were kept within one mm and the electrode resistance was always below 5000 ohms. Records were made from the left occipital and left motor areas at a tape speed of 30 mm/second.

Analysis of Data.—The percent time alpha[4] for the left motor and left occipital area was measured for four different samples of the record, each sample being 50 cm in length, giving a total of 200 cm read for each condition. Alpha waves were defined as potentials falling within a frequency range of 8 to 13 cycles per second, having a minimum voltage of 7μv, and occurring in a series of three or more consecutive waves. The mean of these four samples was taken as the alpha index or percent time alpha for that particular condition. In all cases, simultaneously sampled occipital and motor area EEG's were used.

Results

Tables 1 and 2 present the data for the occipital and motor areas of the four subjects. Each alpha index entered is a mean of five days, based on a total of ten meters of record. In Fig. 1 these data are presented graphically for the left occipital area. The wide inter-individual differences in percent time alpha under resting conditions A, B, and D, and rotational addition with eyes closed are clearly discernible, and certain additional trends may also be pointed out. The two subjects with the highest alpha indices showed a sharp reduction when the eyes were opened; the other two subjects showed smaller reductions. There was a further trend toward lower alpha indices when the subjects were engaged in some more or less specific form of mental work. Finally, there was a trend toward higher alpha indices when the eyes were again closed.

The problem of quantifying these trends may be solved by the methods of analysis of variance and analysis of covariance, supplemented by the *t*-test. These procedures involve an estimate of the intra-individual and inter-individual variability which has been obtained as follows: The variation between subjects (S), within subjects (WS), between days (D), and the 'interaction' variance (S $\times$ D)

[4] This involved the computation of the percentage of time that alpha waves were present on the record. The seeming advantages of the procedure of Williams (27) wherein the total number of alpha waves was computed as a percentage of the total number that *could* appear in that duration of time, are probably offset by the assumption of constant frequency, an assumption which may be difficult to justify.

TABLE 1

MEAN LEFT OCCIPITAL ALPHA INDICES (MEAN OF FIVE DAYS) FOR EACH SUBJECT FOR EACH OF THE NINE CONDITIONS

	Subjects				Diff. for Significance*	
	R.S.	C.P.	J.C.	F.R.	5%	1%
Resting condition A....	87.20	70.00	35.50	10.66	15.19	20.93
Resting condition B....	89.90	65.34	23.36	12.04	10.13	13.95
Resting condition C....	17.40	10.26	22.42	7.94	10.50	14.48
Silent reading.....	10.16	9.40	16.26	2.68	5.54	7.64
Oral reading.....	2.20	4.66	13.44	1.04	4.79	6.60
Talking.....	1.38	9.12	15.72	1.80	5.41	7.46
Rot. add, on, open.....	8.12	18.84	16.30	5.94	13.70	18.87
Rot. add, off, closed...	79.70	43.14	16.70	8.56	15.75	21.70
Resting condition D....	88.00	57.58	21.94	6.84	15.84	21.82

* These columns, and similar ones in succeeding tables, represent the difference in means necessary for significance at the indicated level.

TABLE 2

MEAN LEFT MOTOR ALPHA INDICES (MEAN OF FIVE DAYS) FOR THE NINE CONDITIONS

	Subjects				Diff. for Significance	
	R.S.	C.P.	J.C.	F.R.	5%	1%
Resting condition A....	45.24	39.12	21.48	4.04	10.31	14.21
Resting condition B....	32.74	42.26	19.38	3.12	8.26	11.38
Resting condition C....	13.60	10.36	18.30	3.44	6.82	9.39
Silent reading.....	8.46	8.92	15.20	1.82	3.64	5.02
Oral reading.....	2.14	4.42	12.26	1.02	2.57	3.54
Talking.....	3.76	4.90	10.82	1.14	3.16	4.36
Rot. add, on, open.....	5.80	8.64	10.54	2.58	4.46	6.14
Rot. add, off, closed...	32.44	19.24	16.34	3.74	8.14	11.22
Resting condition D....	35.74	34.60	19.64	2.44	11.21	15.45

was determined separately for each of the nine conditions and for each cortical area. A further analysis was then made for each cortical area by merging all nine conditions in a joint analysis. Stated concisely, these analyses represent the variation for pooled results of repeated experiments with the same subjects on successive days.

The inter-subject variance (S) was compared with the variance for within subjects (WS) and the interaction variance (S × D). The F-ratios for these, and for the evaluation of day-to-day variability are shown in Table 3, together with the magnitude necessary for significance at the one and five percent levels.

For the left occipital area all but two conditions showed significant inter-individual variation, and one of these (resting condition C) was significant at the five percent level. During rotational addition with eyes open, the subjects formed a homogeneous group; the inter-

individual variability was no larger than the intra-individual variability. This means that while most conditions showed significant inter-individual differences, this one condition resulted in such similarity of left occipital alpha indices that these individuals, regardless of initial score, were not reliably differentiated from one another.

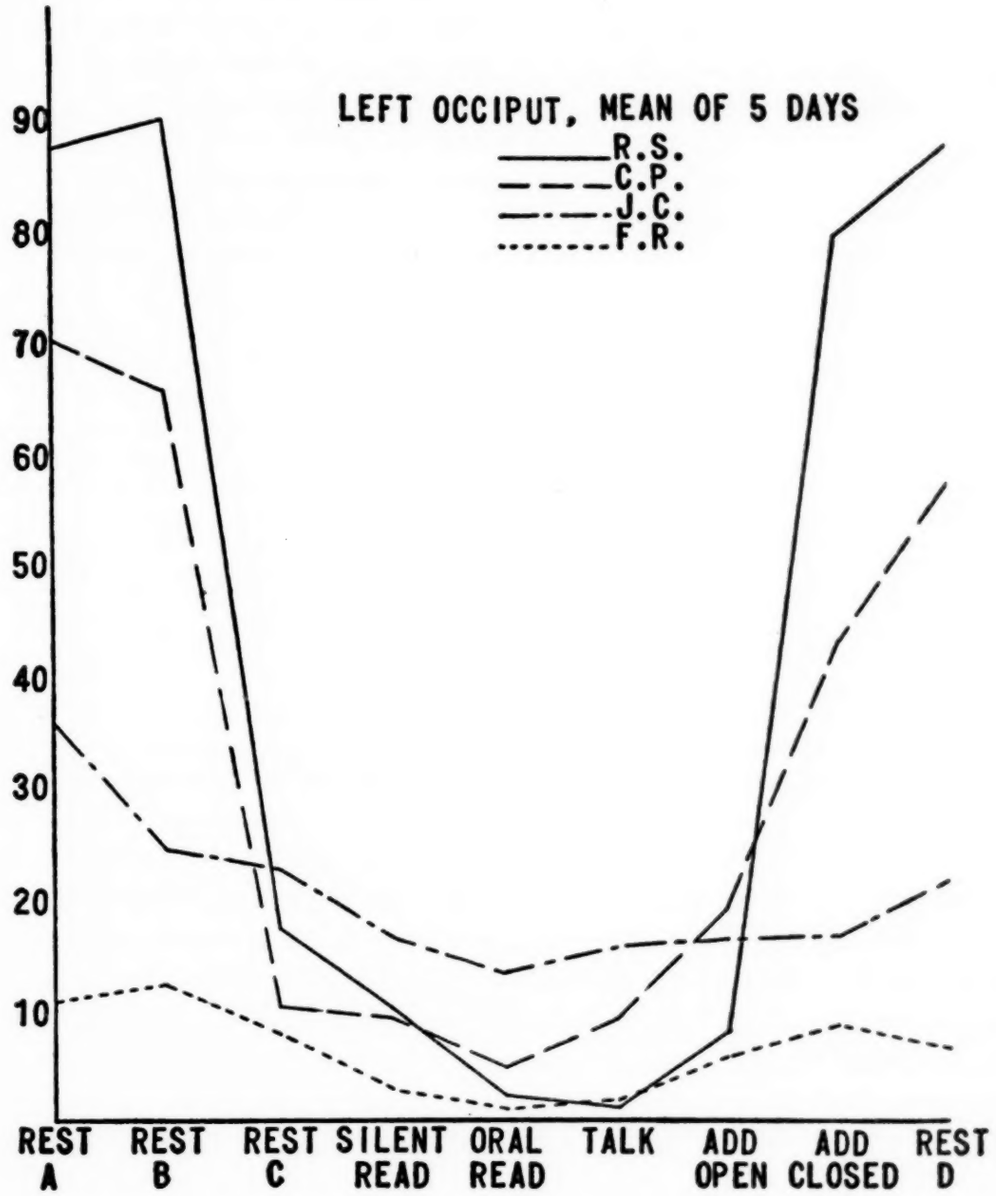

FIG. 1. Mean left occipital percent time alpha (five days) for each of the four subjects (R.S., dominant alpha; C.P., subdominant alpha; J.C., mixed alpha; F.R., rare alpha) in the experimental conditions studied during the waking state. See text for further discussion.

With regard to left motor percent time alpha, the variance ratios are all (but one) significant at the one percent level; the subjects retained their heterogeneity.

That it was justifiable to use the mean of five days as the best estimate available of the 'true' alpha index of the subjects was dem-

onstrated by the fact that the variation from day-to-day was larger than the interaction variance only by chance amounts and frequency.

Since the F-test was, for most conditions, highly significant, it was appropriate to test the significance of the differences between subjects under the several conditions. The last two columns of Tables 1 and 2 show the results of the *t*-test applied to these differences in terms of the amount by which the subjects must differ for the differences to be significant at the five and one percent levels.

TABLE 3

F—Ratios for Analysis of Variance *
(Pooled results of repeated experiments with same subjects on successive days)

	Left Occipital Area			Left Motor Area		
	S/S×D	S/WS	D/S×D	S/S×D	S/WS	D/S×D
Resting condition A....	44.40	45.96	—	32.06	29.20	1.39
Resting condition B....	101.42	115.62	—	36.70	38.06	—
Resting condition C....	4.15	3.59	1.62	6.59	7.54	—
Silent reading.....	10.08	9.03	1.46	48.09	22.03	5.73
Oral reading.....	12.07	12.34	—	32.84	34.96	—
Talking.....	15.69	14.23	1.41	16.93	15.04	1.50
Rot. add, on, open.....	1.75	1.86	—	4.83	5.45	—
Rot. add, off, closed...	36.22	37.21	—	18.42	18.81	—
Resting condition D....	53.32	47.63	1.48	19.42	17.74	1.47
1%.....	5.95	5.29	5.41			
5%.....	3.49	3.24	3.26			

* The magnitude necessary for a given level of significance is listed at the bottom, and applies to each area. The conditions marked — show ratios which were, by inspection, less than unity.

It may be seen (Table 1) that in resting condition A (the 'standard' condition), there was an 'overlap' (one percent level) between subjects RS and CP, while the other subjects were significantly differentiated. In resting condition B ('standard' except for lights on) there was an overlap only between subjects JC and FR. When the eyes were opened *all* subjects overlapped. Only JC and FR failed to overlap under the condition of silent reading. During oral reading only JC was significantly different from *any* of the other subjects. For the condition of talking, RS and FR who were initially at the extremes of the alpha index scale, overlapped and again both showed alpha indices which were significantly lower than JC. *All* subjects overlapped during rotational addition with eyes open, which agrees with the non-significant F-test for that condition. FR and JC overlapped for the remaining two conditions, while the others were all significantly different.

Table 2 shows similar conditions (of overlap) to have occurred for the left motor area except that the subjects were not so clearly differentiated under the control conditions. JC remained signifi-

cantly different from FR throughout the entire series of activities, and showed the (not always significantly) highest alpha index whenever the eyes were opened. Either or both of the subjects with originally highest alpha indices (RS and CP) overlapped the rare alpha subject under all 'eyes open' conditions except that of silent reading.

In short, the *t*-test has shown that whereas under control conditions the overlapping was slight and then only between adjacent subjects, during most of the other conditions the overlap occurred with greater frequency, and, more important, it occurred between subjects who were initially far apart on the percent time alpha scale. This latter point means that the ranks of the subjects' percent time alpha scores have changed in a manner which is not clearly systematic. Although this fact was shown in Fig. 1, it may be further demonstrated by the F-test based on the joint analysis which included all conditions.

The pertinent figures of that analysis are expressed in the following tabulation:

LO Area	LM Area	Levels of Significance	
		1%	5%
3.74	4.58	3.36	2.36
2.13	1.19	1.91	1.59

The first row gives the results of the F-test when the variation in alpha index resulting from the different conditions is tested against the interaction variance. The figures indicate that significant changes in alpha indices did result from the several types of activity. The second row shows the interaction variance tested against the subjects' variance, and reveals that for the left occipital area the changes in percent time alpha are neither proportional to nor determined by the initial percent time alpha. The changes in the left motor area, however, may be accounted for by 'chance' variability based on initial alpha production under standard conditions.

One further point is of some importance: *the reduction in percent time alpha is not entirely due to visual stimulation.* In all cases, both areas showed a significant reduction (one percent level) in group mean alpha indices as soon as the eyes were opened as contrasted with any condition where the eyes were closed. Furthermore, for the left occipital area, the mean alpha index of the four subjects under the condition of oral reading falls below the mean alpha index under resting condition C. The difference is significant at something better than the five percent level. The other conditions of visual

stimulation (eyes open) plus mental work do not show reductions which are reasonably significant.

For the left motor area both oral reading and talking fall significantly below resting condition C at the five percent level. In addition, oral reading falls significantly below silent reading at the same (five percent) level. The *t*-test shows, for both areas, that we may *not* confidently reject the hypothesis that mental work was an important factor in the reduction of group mean percent time alpha.

The techniques of analysis have revealed that there are conditions wherein the heterogeneity of the group has disappeared; that even where heterogeneity is exhibited in the experimental condition it is an expression of a significantly different distribution of alpha indices than that exhibited in the resting condition; and that the change in left occipital percent time alpha is not determined entirely by the magnitude of that measure under 'standard' conditions.

TABLE 4

F—TEST (S/WS) FOR ANALYSIS OF COVARIANCE

	Resting Condition B	Resting Condition C	Silent Reading	Oral Reading	Talking	Rot. Add, On, Open	Rot. Add, Off, Closed	Resting Condition D
Left occipital area	11.28	3.60	8.92	11.58	13.49	2.37	5.45	4.04
Left motor area. .	9.23	6.15	13.04	43.75	14.75	6.69	3.20	4.11

1 percent level 5.42
5 percent level 3.29

In a previous paper it was shown that there was a significant tendency for subjects to regress toward the mid-point of the alpha index scale upon awakening after a night's sleep. The percent time alpha recorded under the standard conditions during ordinary waking states may be *roughly* characteristic for an individual, but at the same time this measure may represent considerable divergence from the theoretical homogeneity of the group upon awakening in the morning. There is thus some justification for assuming that the heterogeneity of the four subjects under the control conditions was due *in part* to chance fluctuations in percent time alpha. It is possible to 'correct' for initial *chance* differences in percent time alpha (resting condition A) and then proceed to evaluate the differences between subjects under the other-than-standard conditions. The correction is easily accomplished by the methods of analysis of covariance.

Table 4 presents the variance ratios which result from such an analysis. For the left occipital area, resting condition C was significant at the five percent level, as was resting condition D. Rota-

tional addition was not significant at any reasonable level. All other conditions were significant at the one percent level, the subjects thereby remaining heterogeneous in these activities. This represents a fair agreement with the results obtained by the analysis of variance. That rotational addition with eyes open represents a condition under which these subjects became a homogeneous population with regard to left occipital alpha index is further substantiated. Resting condition C is again heterogeneous at a lower level of confidence. Resting condition D, however, is now revealed as significant at but the five percent level, whereas it was highly significant under the analysis of variance. This means that the initial 'chance' differences in alpha index may have served to mask the (not entirely significant) trend toward homogeneity now revealed in resting condition D. This is important in view of the fact that resting conditions A and D are both presumably 'standard' conditions.

The analysis of covariance revealed two conditions of marginal significance for the left motor area. Rotational addition with eyes closed was significant at slightly short of the five percent level and resting condition D was significant at better than the five percent level. This latter is in agreement with the results from the left occipital area. There are reasons both for and against an expectation that the left motor and occipital areas should be concomitantly significant or non-significant under a given condition. The alpha indices of the two areas do tend to vary together, but it has been shown by other workers (**12**, **21**) that they can, and often do, vary independently.

When the F-test was applied to these data the null hypothesis being tested was that there were no real differences between subjects after allowances had been made for *chance* fluctuations in initial mean alpha indices. Since the F-tests were often significant, the *t*-test should be applied for precisely the same reasons it was used with the analysis of variance.

Essentially similar results were obtained; the subject means under resting condition A (left occipital area) were all significantly different at the one percent level. In each of the succeeding conditions there was an overlap between one or more of the subjects, meaning that they were no longer reliably differentiated. Even more overlapping occurred for the left motor area. Again, for both areas, any significant differences that were retained were not systematically related to the original ranking of the subjects regarding percent time alpha. It was not possible to predict the relative amount of change in percent time alpha that would occur under these other-than-standard conditions.

Discussion

Most of the statements in the literature regarding the constancy or the individuality of the alpha rhythm are based on recordings secured under essentially 'standard' conditions, and research directed toward an extension of these statements has only recently begun to appear.

Rubin (**22**), in an analysis of variance of the occipital alpha rhythm in normal and schizophrenic subjects, found insignificant variations in percent time alpha within a given experimental session ('standard' conditions only). He found that the measure showed significant variation from day-to-day, but was able to conclude that ". . . in spite of the significant day-to-day variation, the mean percent time alpha is characteristic for an individual" (p. 328). He found the measure to be accurate within fifteen percent time alpha, with less variation for subjects with high and low indices.

That the present study does not substantiate Rubin's finding of significant day-to-day variation is likely due to two general sets of facts. First, the separate days in these experiments were probably more comparable, since a specific effort was made to record the subjects at the same time daily, and to have them follow as constant a physiological routine as possible during the five experimental days. Second, Rubin dealt with a continuum of alpha indices and only one condition, while this study used subjects selected to be widely separated on the scale and a wide variety of conditions. His further conclusion, that the measure is characteristic for an individual, was based on the finding that the variation between individuals was significantly greater than the average day-to-day variation of a given individual. No data are given regarding the significance of individual or group means.[5]

Williams (**27**) in a study of psychological correlates of the EEG concluded that

> . . . when a change in the amount of alpha activity occurs concomitant with a modification of psychological states, the change which takes place is uniform because it is generally consistent in direction and proportional in degree for all subjects. It is possible, therefore, to discount individual differences in the initial amount of alpha activity because they do not distort the changes we are interested in (p. 24–25).

His conditions included the 'standard' condition, eyes open under illumination, silent reading, and over-ventilation, and his conclusions were based on rank difference correlations.

[5] It should be noted that in the present study such data, based on the *t*-test, made it necessary to qualify any conclusions pertaining to the retention of population heterogeneity, which might be drawn from the F-test alone. Significant inter-individual differences were common enough, but they were not consistently related to the same type of heterogeneity that existed under 'standard' conditions.

It is quite possible that such conclusions differ from those that might be drawn from the present study not because of differences in the raw data, but because of differences in techniques of analysis. His conclusions were based on the assumption that the statistic used was adequate to deal with his data. The P.M. vs. A.M. alpha index correlation (rho) of .58 ± .11 previously reported is particularly germane to this point of statistical methodology. Williams obtained a rank difference correlation of .63 ± .08 between the 'standard' condition and the condition of sitting quietly with eyes open under illumination. The respective N's were 19 and 28. In the present study an analysis of variance was done as a supplement to the P.M. vs. A.M. correlation. This revealed that while before sleep the groups of subjects formed a heterogeneous population, after awakening a homogeneous population was evidenced and adjacent groups were not significantly differentiated along the scale.

It is not possible to state whether or not a similar analysis of Williams' data would indicate similar results, but the parallel is interesting. (In fairness it must be said that since the trend in his data was in one direction—reduction—, rather than toward a mid-point, similar results might not be obtained upon further analysis.)

In general, however, these results are probably not in serious conflict with those of Rubin and of Williams, and those of Davis and Davis (**2**) and Travis and Gottlober (**24**). The carefully chosen wide variety of subjects and experimental procedures herein used were directed specifically toward exposing such homogeneity as might be present. The several conditions wherein it occurred in this and in the earlier paper are considered as constituting evidence in support of the hypothesis of Knott, *et al.*, that as the 'psychological' differences between individuals are reduced, so are their electroencephalographic differences.[6]

Summary and Conclusions

1. An attempt has been made to determine whether individual differences in the alpha index of the EEG are the reflection of fixed, unalterable and perhaps genetically determined characteristics, or whether these differences may change or perhaps disappear as the individuals are engaged in various types of psychological activities.

[6] It is recognized that this comes close to being a case of reasoning after the fact. The selection of conditions to include those of similarity for all subjects was of necessity done on *a priori* bases. Likewise, their effect on the EEG was unknown until after the data were collected and evaluated. It is unfortunate that we have no way of knowing whether the conditions of electroencephalographic similarity were also conditions of exceptional 'psychological' similarity. However, it seems reasonable to propose a greater degree of 'psychological' similarity during the execution of similar tasks than during the 'standard' conditions, in which there is no direction of psychological activity whatsoever.

2. A wide variety of experimental conditions and a wide variety of subjects have been employed in an attempt to offer opportunity for the appearance (or disappearance) of important changes in the EEG.

3. The percent time alpha has been utilized as the index of the EEG with the realization that it encompasses only one aspect of the total record.

4. What appear to be the most adequate statistical techniques available for the evaluation of such data have been used.

5. Certain conditions of psychological activity coupled with visual stimulation resulted in the reduction of inter-individual differences to the point where they did not significantly exceed intra-individual differences.

6. Inter-individual differences in many conditions, when maintained, were the expression of a *different* heterogeneity than found under control conditions.

7. It was not possible to predict accurately from this measure obtained under 'standard' conditions, the type and distribution of changes in percent time alpha occurring under other conditions.

8. These findings are considered as offering some support to the hypothesis that a reduction of 'psychological' individual differences may be accompanied by a reduction of electroencephalographic individual differences.

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VOLUNTARY RESPONSE TO VESTIBULAR STIMULATION WITH SMALL AMPLITUDES OF PASSIVE ROTARY OSCILLATION

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The problem of the nature of labyrinthine stimulation and the characteristics of the consequent organismic response has an important bearing today in view of the great developments in aviation. Recent refinements in the stimulation of the static receptors and in recording the resulting behavior will, we hope, add a new chapter in general human psychophysiology. The question as to just what constitutes a stimulus of the vestibular senses in the passive or active movements of the body is crucial in the analysis of the perceptual and adjustmental factors of bodily movements in space.

Several studies made by Dodge (1), Travis and Dodge (2), and Gurnee (3) showed that the adequate stimulus for vestibular excitation is either positive or negative acceleration in the movements of the body. Rectilinear passive body motion at a constant velocity would not be perceived at all in case extra-labyrinthine excitation is controlled. Rotary body motion at a constant velocity subjects the body to centrifugal force, thus stimulating the pressure senses throughout the body as well as producing a special type of stimulation of the static senses. Slowing down and speeding up of bodily motion are the essential factors in vestibular stimulation. In view of the fact that all movements of the body have a beginning and an ending, thus exhibiting positive and negative acceleration, the vestibular receptors are almost continuously excited.

The relative sensitivity of the organism to body movements in a straight line and movements around an axis was studied by Travis and Dodge in 1927 (2). Those results showed that sensitivity to passive rotary oscillation was at least sixty times as adequate as sensitivity to passive rectilinear motion. In these early studies careful consideration was given to controlling the visual, the auditory, the cutaneous, and the kinesthetic sense fields. Control of visual and auditory cues was easily accomplished. The best means of controlling the cutaneous and the kinesthetic senses was to truss the trunk and limbs securely to the rotation platform in a fashion that the small amount of change in pressure in the acceleration and deceleration phases of the passive oscillation of the body would be imperceptible. It has long been known that the cutaneous and

kinesthetic senses play a highly significant role in the normal perception of space and in equilibratory adjustments in the active and passive movements of the body.

All writers of psychology textbooks carefully avoid the real problems of vestibular stimulation and consequent adjustment by stating that several sense fields combine in some unanalyzable fashion in static and dynamic equilibrium. Our experiments, beginning with those of Dodge, have shown (1) that perceptual thresholds in passive movements of the body can readily be obtained, (2) that kinesthesis and cutaneous sensitivity can be sufficiently suppressed or controlled to obtain almost pure vestibular responses, and (3) cutaneous and kinesthetic cues under certain controls provide great reënforcement in the perception of body motion. We have come a long distance from the crude observation of optic nystagmus following several revolutions on the Bärany chair to the refined presentation of simple harmonic motion which can be accurately controlled as to the speed and magnitude of movement.

The question as to what part or phase of a bodily movement constitutes the real stimulus in eliciting a vestibular response is important in any experimental study of the perception of body motion. This question is all the more important in our refined technique in the use of successive phases of simple harmonic motion. Specifically, are the acceleration and the deceleration phases reacted to separately and individually or is the total movement reacted to as a single stimulus? The present report bears directly on the answer to this question.

The technique employed in this study was the Dodge rotation platform which was oscillated by an electric motor through a crank and pulley. This procedure provides stimulation of the vestibular receptors and this type of motion approximates closely the sine-wave motion of a pendulum. This smooth regular type of oscillation can be easily controlled regarding amplitude and acceleration. The subject was blindfolded and his voluntary manual response together with the oscillations of the platform were recorded on a smoked drum. Amplitudes of $\frac{1}{4}$ degree, $\frac{1}{2}$ degree and 1 degree with average velocities of 0.27, 0.47, 0.55, 0.70, 0.80, 0.95, 1.32, 1.40 and 1.86 degrees per second respectively were used in the present study. Twenty-one college men acted as subjects.

The subject was instructed to move the recording stylus to the left if he perceived movement to the right, and not only move the stylus to the left but move it at the same rate of speed and to the same extent as the perceived movement. These conditions, of course, were reversed in case of passive body movement to the left. Each

subject was given a short preliminary practice trial to acquaint him with the task.

In the oscillation of the platform upon which the subject was seated three different rates of oscillation for each of the three amplitudes were used. The nine combinations of rates and amplitudes, together with two non-stimulation periods, made up a total of eleven trials for each subject which were presented at random with a short rest period between trials. The two non-stimulation periods were given to aid in breaking up any rhythmic set which the subjects were inclined to adopt in responding to real or apparent movement of

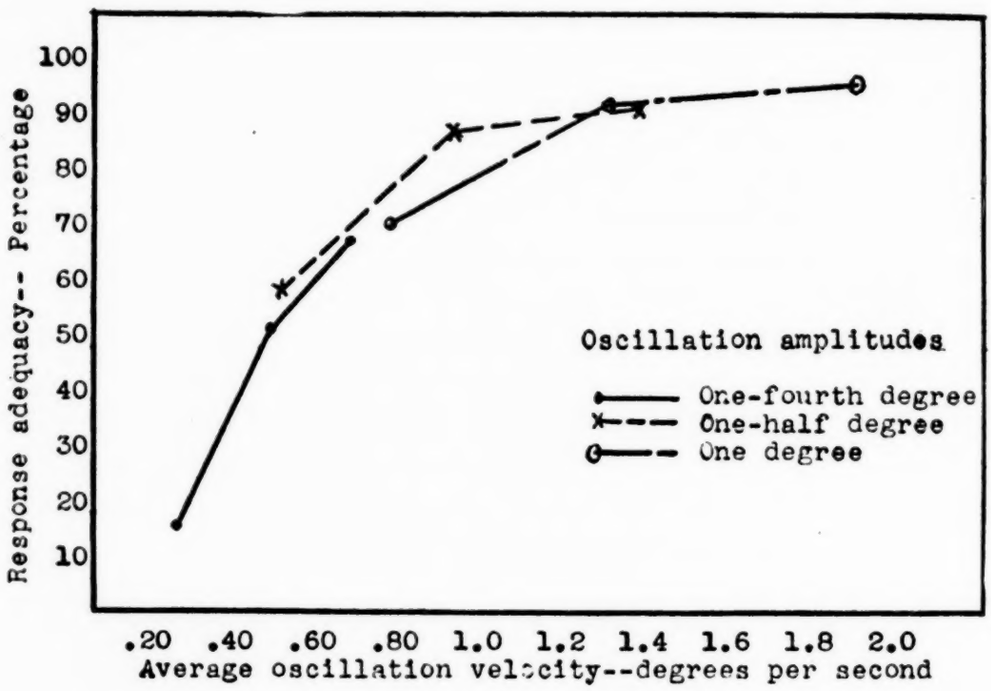

FIG. 1. Relationship between average velocity of oscillation and adequacy of voluntary response in percentage for three amplitudes of oscillation. The three frequencies of oscillation were identical for all three amplitudes, however, acceleration and velocity are functions of both amplitude and frequency of oscillation (N = 21).

the body. There were a few responses to illusory movements during the non-stimulation periods. These responses rarely duplicate in rhythm the oscillations of the stimulation periods.

In summarizing the results in graphic form in terms of adequacy of response to the perception of passive rotary oscillation with varying rates of oscillation and various amplitudes, certain rather definite relationships were apparent.

The ordinate gives the percentage of correct response, the abscissa the average velocity in degrees per second. Average velocity in harmonic motion means very little. The important factor is acceleration. However, it is much simpler to express the speed of oscillation

in terms of average velocity in view of the fact that as the velocity increases in harmonic oscillation the acceleration increases also.

No subject at any time responded to the acceleration phase and deceleration phase as independent stimuli. The rotary movement to the left and the rotary movement to the right were responded to as single stimuli despite the fact that each had an acceleration and deceleration phase.

The following conclusions from this study seem justified:

(1) The magnitude of change in acceleration and deceleration was the significant factor in vestibular stimulation.

(2) Changes in amplitude *per se* did not effect adequacy of response to successive half oscillations. In other words, a passive movement of the body comprising an acceleration phase and a deceleration phase is interpreted and reacted to by the organism as a single stimulus of motion within our experimental limits of from $\frac{1}{4}$ degree to 1 degree. Previous studies by Dodge and Travis using amplitudes up to 8 degrees were in line with these results.

(3) The curve of relationship between adequacy of voluntary response and average velocity (indirect measure of acceleration) shows a direct relationship between these two functions irrespective of the changes in amplitude of oscillation. That is, the rate of change of motion is the essential factor in vestibular stimulation and not the extent of movement.

(4) The 75 percent threshold for the perception of rotary oscillation in terms of average velocity was about 0.90 degrees per second. These results with small amplitudes correspond to earlier findings with large amplitudes of oscillation.

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THE INFLUENCE OF AGE ON THE FUSION FREQUENCY OF FLICKER *

BY ERNST SIMONSON, NORBERT ENZER, AND SAMUEL S. BLANKSTEIN

The fusion frequency of flicker is defined as that rate of successive stimuli which is just necessary to produce complete fusion and has the same effect as a continuous illumination [Duke-Elder (3)]. Cobb (1), Riddell (8), and Ferree and Rand (4) surmised that a decrease in the fusion frequency occurs with age. These authors emphasized the importance of further studies in this direction because the number of subjects (5 in Riddell's investigation) was much too small to afford any definite conclusions.

The flicker phenomenon is considered as one of the most fundamental of visual functions [Crozier (2), Hecht (6)] in which retinal processes and their representation in the visual centers are of equal importance. In view of the above facts, in attempting to apply the flicker phenomenon as a sensitive test for the excitability of the visual pathways as a whole, it was felt that the influence of age on it should be more extensively analyzed.

The flicker phenomenon would in this manner permit us to determine the effect of age on a principal sensory function of the central nervous system. All measurable visual functions such as visual fields, speed of dark adaptation, and minimal threshold of light perception, are lowered in the aged [Ferree and Rand (4)] but have not been extensively investigated to make a statistical analysis of the average rate of progress of this decline.

Method

We used a rotator arrangement where the beam of light from an electric bulb (25 watt Mazda, the voltage of which was kept constant by a voltage regulator) was interrupted by a rotating disk with four identical openings. The light was projected onto an opal glass to obtain proper diffusion. The speed of the rotating disk could be changed minutely and measured by a mechanical revolution counter with a stop watch. The openings were of a different size in each of the disks in order to vary the relationship of the duration of the flashes to the duration of the dark intervals. The relative duration of flashes, expressed in percent of a single whole cycle, in the three disks used in this series was 64 percent, 27 percent, and 17.7 percent.

The subject was seated with his head placed on a chin rest so that the distance from the illuminated area to the eye was kept constantly at one meter. We investigated the subjects under the following standard conditions: The vertical intensity of illumination of the surroundings at the plane of the illuminated area was 2.0 foot-candles. The vertical intensity of illumination at the subject's face was 0.32 foot-candles; the size of the illuminated area was 100 sq mm equivalent to a visual angle of 1/2 degree. The intensity of illumination of the test-patch area was 0.0009 candle power per sq cm for 17.7 percent relative duration of flashes, 0.0014 candle power for 27 percent, and 0.0033 candle power per sq cm 64 percent. Binocular central vision was used.

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Our results concern exclusively the fovea because the size of test area was well within limits of the size of the fovea. The time of exposure was limited to 1.5 seconds which Riddell (8) considered to be the physiological optimum.

Under these standard conditions forty-seven normal subjects whose ages ranged from fourteen to eighty years were investigated. The vision and ocular structures of each of these subjects were normal in all respects. The sex was equally divided.

The accuracy with which the values could be reproduced was high. As the values were rechecked the variation taken in the same experiment exceeded only in exceptional cases 11.5 flashes. Where the findings were checked on different days the variations did not exceed ±2 flashes, provided that the subject's general condition was the same. The onset of an upper respiratory infection, such as a cold or presence of considerable fatigue from various causes definitely decreased the fusion frequency. On the other hand, we found that the discrimination of flicker could not be improved by training. O'Brien's (7) experience has been the same.

Results

We divided our material into four age groups, 10–19 years, 20–29 years, 30–39 years, and those over 40 years of age. The maximum value, the minimum value, and the average of each of the age groups is shown in Table I when the duration of flashes was 64 percent of a single cycle.

TABLE I

Maximum, Minimum, and Average Values of Fusion Frequency in Four Age Groups

Age (years)	No. of Subjects	Min.	Max.	Aver.
10–19	4	41.0	53.9	45.9
20–29	18	40.8	54.1	46.2
30–39	10	40.8	46.7	44.4
40	15	40.4	45.0	42.3
All Groups	47	40.4	54.1	44.9

Table I shows no differences between the minimum values in the different age groups [*i.e.*, in the younger age groups as low values may be obtained as in the older age groups].

There is a definite influence of age on the maximum and the average values. The highest values were obtained in the age group of 20–29, from which the fusion frequency progressively decreases with age (Fig. 1). Thus, the highest values in age group 10–29 are not found in the age group over 30. The difference is greater than the daily variations of a single individual (±2 flashes) and far beyond the experimental error (± 1 flash per second).

The distribution of the individual values is analyzed as follows: The average of all subjects of all age groups was 44.9 flashes per second which has been used for the distribution of the values of the different age groups. The average value of all subjects (44.9) was practically identical with the highest value in the age group over 40 (45 flashes per second), found in one of the subjects of this group.

The other fourteen subjects of this age group had results all below this value. In the age group 30–39, three subjects have higher and seven subjects lower values than forty-five flashes per second. Of the twenty-three subjects in age group 10–29 in twelve the fusion frequency was higher and in eleven lower than 45.0. This shows that there is a gradual shifting in the distribution from higher to lower values with age. Consequently, the mean values decreased with the age, as shown in Table I and Fig. 1.

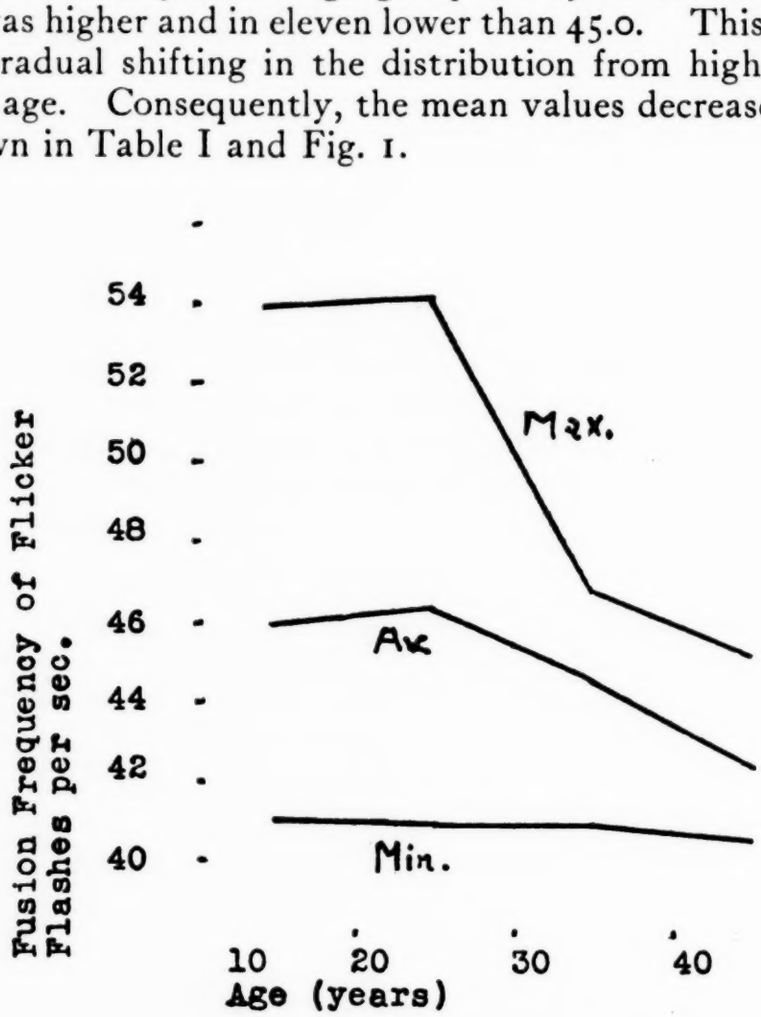

FIG. 1. Maximum, minimum, and average value of fusion frequency of flicker in four age groups.

The minimum, maximum, and average values of the age group 10–19 and 20–29 were equal within the experimental error. The range of the values found in the age group of 10–30 covers all the values found in the older age groups; likewise the range in the age group of 30–39 covers all the values found in any subject of the age group over forty. This means that the range of values found diminishes with age (Fig. 1). The standard deviation calculated also diminishes with age. It is ± 4.5 for age group 10–29, with a standard error of 0.94; it is ± 2.01 for age group 30–39, with the standard error of 0.67; and it is only ± 1.4 for the age group over forty, with the standard error of 0.40. The difference of the mean values is not significant from a statistical point of view due to the large standard deviation in the age group 10–29. These figures are nothing

else than the mathematical expression of our statement that the values in the younger age groups may be as low as in the older age groups. On the other hand, the higher values under the age of forty that are over 45.0 exceed the mean value (42.4) of the age group over forty by more than five times the standard error of this age group. This is mathematically significant. Identical results with similar decrease of the values have been obtained with a relative duration of flashes of 27 percent and of 17.5 percent of the whole cycle at a higher absolute rate of fusion frequency.

We feel that the average decrease of the fusion frequency of flicker is not directly related to the fact that a decrease in visual acuity occurs with age [Friedenwald (**5**)]. The visual acuity begins to diminish after the age of forty and is only slight until the age of fifty. However, the average decrease in fusion frequency is already in evidence after the age of thirty. On the other hand, in about one-half of our subjects in the age group 10–29, the values were quite low, while the visual acuity was definitely normal. Therefore, the low values could not be correlated to any age factor.

Summary

This study shows that there is a general definite decrease of fusion frequency with age as demonstrated by the average and maximum values. The high values found in about half of the subjects between ten and twenty-nine years cannot be obtained in the older age groups, but on the other hand, in the young as low values may be obtained as in the older age groups. These results show a decrease of a fundamental sensory function of the central nervous system with age.

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COMPOSITE STEREOGRAPHY: A TECHNIQUE FOR PRODUCING BINOCULAR DEPTH PERCEPTION WITHOUT PAIRED STEREOGRAMS OR VIEWING APPARATUS

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Under ordinary conditions of observation, the binocular images from any object in the visual field are disparate in character, due to the separation of the two eyes in the head, and fall on corresponding points of the two retinæ. This disparity in horizontal pattern, through a complex process of inter-sensory conditioning involving particularly visual, auditory, tactual, and kinæsthetic stimulation, has come to serve as a cue for the immediate visual perception of depth, solidity, or tri-dimensionality.

The basic mechanism involved is demonstrated by means of the stereoscope, which experimentally reproduces the conditions for depth perception in a simple and exaggerated form. Psychologists and others in related fields have developed a number of methods—usually involving modifications of the stereoscope—for demonstrating different binocular tri-dimensional effects. Among the best-known of such techniques or devices may be mentioned: free stereoscopy (convergent squinting); the stereoscope (box, tube, lens or prism, mirror or reflecting, etc.) and tropostereoscope; the telestereoscope (prism, mirror or reflecting, etc.); the iconoscope or inverted telestereoscope; the pseudoscope (total reflexion, converting, mirror, lenticular, etc.) and perspectoscope; projected stereograms with alternating shutter; anaglyphs and plastographs (with lorgnette filters variously known as anaglyphoscope, 'orthoscope,' 'macyscope,' etc.); polaroid stereography; the parallax stereogram or double negative method; the integral picture; and the parallax panoramagram or composite stereography.

Techniques Requiring No Special Viewing Apparatus [1]

It will be noted that with the exception of the last three devices mentioned, all of the above instruments or techniques make use of a pair of stereograms and/or a more or less elaborate viewing apparatus, such as a stereoscope or similar device, an alternating shutter, colored or polaroid filters to be used as lorgnettes, and the like. The *parallax stereogram* or '*double negative*' *method*, developed in 1903 by F. E. Ives,[2] represents the first step in an effort to dispense with the viewing device as a necessary means for properly directing the two disparate images to their respective eyes. It consists of a transparent picture, composed of narrow juxtaposed strips which are of two families, each family being printed from the respective members of a stereoscopic pair. In front of, and slightly separated from this transparency with alternating strip images, is a grating consisting of opaque and transparent spaces, so placed that an eye in one position sees only one set of strips, in another position only the other set. By making the picture strips fine enough to fuse at the viewing distance and by properly choosing the grating distance and spacing, stereoscopic vision is achieved without the use of a stereoscope, although the effect is limited to one correct viewing position and distance.

Escape from the limitation in the range of observing distances and positions characteristic of the parallax stereogram was made by Lippmann in 1908 in his *integral picture*. In place of extremely narrow lines in a grating, Lippmann proposed the use of pinholes, behind each of which was mounted a complete transparent pinhole picture of the object, each picture differing stereoscopically from its neighbors both vertically and horizontally. In order to admit more light, he suggested that the pinhole grating could be replaced by a structure containing a large number of small convex lenses formed on the front surface of a layer of transparent refracting medium, the back surface of which was to be coated with photographic emulsion so that the multi-image pictures could be developed. When viewed from any position, a composite image would be built up, provided the lens elements were sufficiently small, which would be different from the composite image seen from any other position. Thus in binocular vision the picutre would appear stereoscopic from any position or direction. Although Lippmann suggested several photographic procedures for making the integral picture, the theoretical aspects were not completely worked out or practically realized, although experimental

[1] For a more detailed discussion of these methods, which is unfortunately lacking in the psychological literature, the reader is referred to Ives, H. E., Pan-stereoscopic photography and kinematography, *Photographic J.* (Royal Photographic Society of London), 1933, **73**, 482–496.

[2] Ives, F. E., United States patent No. 725, 567, issued in 1903.

demonstrations of the principle involved have been made by H. E. Ives and others.

Since the human eyes are always in a horizontal plane, the only practical interest is in the horizontal disparity of images necessary for stereoscopic relief. To produce variation of appearance with motion of the observer in the horizontal plane is the aim of the *parallax panoramagram*, which was historically developed from the parallax stereogram, although logically derived from the integral picture, with which it may be contrasted. Instead of pinholes, slits are used; and instead of convex (or concave) spherical lenticular elements, corresponding cylindrical elements are employed. Typically, in making the parallax panoramagram, a large diameter lens is used in conjunction with an opaque line grating, each part of the lens contributing an elementary linear element, representing a different point of view, to the panoramic strip behind each slit in the grating. Positive transparencies from these negatives are then mounted with similar gratings which are placed behind and separated from the photographic layer. A concave mirror can be substituted for the lens in order to increase the angle through which the parallax panoramagram will exhibit relief. Since an opaque line grating has the objection that the picture requires considerable light for viewing, the grating may be replaced by a cylindrical lens structure, *i.e.*, a ridged sheet of convex lenticular elements. Various techniques may be employed to obtain the necessary stereoscopic (orthoscopic rather than pseudoscopic) effect, as well as to obtain opaque pictures for viewing by reflected light, instead of transparencies viewed with a diffused light source behind them. Thus in the case of parallax panoramagrams made with a lenticularly ridged grating, if an opaque photographic print be substituted for the transparent emulsion, light coming through the ridges from any direction will be reflected back in the necessary directions, and the pictures can be viewed as one would view an ordinary photograph.

In order to achieve a panoramic series of views in the horizontal plane, several different methods have been employed. One such technique involves the use of a *battery of closely juxtaposed cameras* in which a large number of negatives are taken simultaneously, from which the images may be simultaneously projected upon a grating and slightly separated plate. Another method, originally used by Kanolt,[3] involves the use of a *moving camera.* Kanolt moved the camera in an arc about the object, and simultaneously moved an opaque line grating in contact with a photographic plate through the distance corresponding to the separation between the narrow clear lines of his grating. In other forms of moving-lens camera, the grat-

[3] Kanolt, C. W., United States patent No. 1,260,682, issued in 1918.

ing and photographic plate are clamped together with a small separation, and the motion of the lens develops the strip panoramas by sweeping the beam of light from the grating slits across the plate, proper precautions being taken that these strips are correctly oriented so as to give stereoscopic relief. Or, a simple motion picture camera may be arranged to move in an arc about the object during exposure, the negative film so obtained being subsequently projected upon the lenticulated sheet and the camera being similarly moved during the exposure.

The Present Technique: Composite Stereography

The present paper describes a film, developed by The Douglas F. Winnek Laboratory, Mount Vernon, New York, which represents an extension of the moving-camera technique for obtaining a parallax panoramagram. The resulting film, or 'composite stereograph,' thus dispenses with the pair of stereographic pictures and with any intermediary viewing apparatus, and embodies the advantages of a stereoscope combined with photographic film. Since the psychological conditions for binocular depth perception are met, however, the tridimensional effect is achieved by viewing the film with the unaided eyes. The salient features of the technique should thus be of interest to all experimental psychologists.

1. *Film and Processing*

The film used is ordinary photographic film which has been embossed on the base side with microscopically small lens ridges or lenticulations. These minute ridges applied to the acetate (or other) base of the film have a definite lens action upon incident light. The ridges are applied by momentarily softening the base of the film and impressing 200 ridges per square inch, of a definite curvature, upon it.[4] The resulting surface becomes an integral part of an optical system when placed between the observer's eye or the lens of a camera and the emulsion (picture) side of the film. Either chromatic or achromatic film may be employed.

2. *Exposure*

The film is exposed in a scanning camera, lenticular side toward the lens. During the process of exposure, the camera is moved across the object photographed. When a panoramic series of views of the object thus photographed are projected into the lenticulated film by the laterally moving camera lens, each view is contracted into linear

[4] Winnek, D. F., United States patent No. 2,218,227.

elements on the photographic emulsion by the lens action of the ridges. These picture elements are disparate in nature and are not superimposed, but are laterally or panoramically displaced, forming a composite stereograph. This is accomplished through the simultaneous action of the camera lens, the lens action of the lenticulations, and the scanning of the camera. When viewed through the same ridges, the panoramic series of contracted, disparate picture elements (one for each ridge) reappear and resolve into undistorted panoramic views of the photographed object.

3. *Phenomena Observed*

The exposed film is processed by ordinary means. It consists of a lenticulated base through which the film is viewed and an exposed emulsion which contains built up behind each lenticulation a view of the object from a slightly displaced viewpoint. The film is observed with the lenticular side toward the eyes. Here again, because of the lens action of the lenticulations in conjunction with the separation of the eyes, the observer is able to see slightly different views with each eye, thus producing the various impressions associated with binocular depth perception. Stated more specifically, the lens action of the lenticulations results in the right eye seeing only one view of the panoramic series, and the left eye another view. There is thus presented to each eye a view corresponding to the view which it would get were it actually seeing the original object: the observer therefore perceives depth, since disparate images are falling upon corresponding points of the retinæ. When the observer moves his head across the film to another position, each eye sees a different picture from the one it previously saw. Because the picture (emulsion) side of the film contains a panoramic series of views, from each position at which the observer places his head he sees a stereoscopic pair; consequently he can look around and beyond each plane in the picture exactly as he would upon viewing the original object directly.

There are several interesting psychological phenomena to be observed while viewing the film. Most prominent, of course, is the illusion of depth and the impression that the viewed image is a real, molded three-dimensional object. In this connection it is also found that the observer can actually see around and beyond objects in the foreground. Stated in another way, objects in the foreground appear to move with relation to objects in the background when the viewpoint is shifted. This 'movement perspective' or parallax phenomenon, involving the relative movement of near and far objects, has long been recognized by psychologists as an additional cue in normal binocular depth perception. It is interesting to note that this par-

ticular cue is *not* available in the ordinary stereoscope. This characteristic of the present film enables one to make depth measurements directly from photographs, since by formula, the movement of a superimposed grid against objects in the foreground or background of the picture may be translated into depth measurements.[5]

Similar perceptual phenomena can be demonstrated by marking the film in various ways. Thus if a pencil point is placed on some object in the picture, such as the center of a flower, the flower will appear to project out and beyond the pencil point. Another trick is to attempt to place the pencil point, without success, on an object in the background of the picture.

Recently another interesting phenomenon has been observed at the Winnek laboratories. In connection with motion studies, it was found that if a composite stereographic picture be taken of a set of meshed gears while they are in motion, the gears will actually move in the finished photograph when the viewpoint is shifted laterally or when the film is rotated on its vertical axis. Thus actions such as the bringing of a cigarette to the lips, the winking of an eye, the rotation of a clenched fist, etc., have been recorded on the lenticular film and the motion studied in three dimensions. Experimental psychologists will at once recognize this as the *phi phenomenon*, or phenomenon of apparent motion, studied extensively by Wertheimer, Korte, and others and illustrated in everyday life by the cinema, illuminated ads, and the like. Any stimulus-object moving across the visual field will stimulate successive points along the retina at successive intervals of time, *i.e.*, the perception of motion involves successive temporal stimulation of spatially disparate points. Hence the illusion of apparent motion, or phi phenomenon, can be demonstrated experimentally by successively stimulating spatially disparate points along the retina at rapid intervals with stationary stimuli. In the present instance, the apparent motion is produced by shifting the viewpoint or by rotating the lenticulated film on its vertical axis, thereby rapidly stimulating successive points on the retina by stationary (and tri-dimensionally perceived) pictures; since these pictures were taken of a moving object at successive intervals of time, during the sweep of the scanning camera, they are *progressively* disparate, and thus give rise to stimulation of successively disparate retinal points and to the apparent movement of the object in the picture. The unique [6] feature of the present situation is that the perception of both depth and apparent motion is achieved by means of a single composite stereograph.

[5] *Cf.* later section on *Applications*.

[6] As far as can be ascertained, this phenomenon has not been previously reported in the psychological or photographic literature.

4. *Applications*

The value of the composite stereographic picture for instruction and research, especially in the biological sciences, cannot be overestimated. The process, moreover, has been applied to several fields of photography in addition to straight portrait and still-life work, *viz.*, aerial photography and x-ray radiography.[7] The process may also be applied in the making of positive prints having the same three-dimensional qualities. The use of composite stereographic time and motion studies, although a matter for future development, should prove invaluable in industrial and other fields of psychotechnology, as well as in the physical and biological sciences generally.

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[7] In diagnostic radiography it is advantageous to observe structures modelled in three dimensions and to measure their depths. The value of seeing into foramina, around bone articulations and crests, and of observing spines and processes standing out in bold relief is evident, as is the need for accurate means of measuring fracture magnitudes, linear and angular bone displacements, and the depths of foreign bodies. 'Trivision radiography' offers a quick and accurate method of determining length, breadth, and depth from a single radiograph, without the need for stereoscopic pairs with the attendant complex viewing devices and tedious measuring technique. It enables the diagnostician not only to see particular structures in natural three-dimensional relation to each other, but also to obtain directly from the picture such critical depth measurements as those involving the clavicle and scapula, ribs and scapula, pelvis and sacrum, sternum and vertebræ, etc. Other equally important measurements involving the depths of organs and systems will at once be apparent.

The application of the process to radiography requires that a series of views of the subject photographed be projected into the film by visible light, in order that the lenticulations may refract. This is accomplished by using a planigraph with the film cassette replaced by a fluorescent screen, and by photographing this screen with a scanning camera. The planigraph produces a panoramic series of views of the subject on the fluorescent screen, and these in turn are recorded by the camera on the lenticulated film.

The height, width, and depth of a subject are accurately recorded in such a trivision radiograph. Should the picture be smaller or larger than the subject, the three dimensions are proportionately smaller or larger. A measure of the height or width of the image on the film corresponds to the measurement of the height or width of its subject on the subject plane. Depth distances between planes in the subject are revealed as a displacement between the two positions held by an image plane in the two extreme panoramic views and the measuring grid which is printed or superimposed on the emulsion plane of the film. The plane upon which the grid appears superimposed is the datum plane held by the point of rotation in the camera. The measuring grid is cross ruled at 1 mm intervals, with darker rulings at 1 cm intervals. In the radiograph the grid divides the image into square millimeter sections. The length-breadth position of any structure may be read directly from the grid when the film-fluoroscopic screen ratio and tube position permit 1 : 1 ratio for size. When the radiograph is an enlargement or reduction of the subject, correct measurements of length and breadth are found by multiplying the grid reading by the magnification or reduction factor.

The measurement of depth involves a recognition of the principle that objects in three dimensions are displaced with relation to each other when the viewpoint is shifted laterally. The observer simply views the image through the ocular first from one 'flick' position and then from the next 'flick' position, and notes the visible displacement of the subject point against the millimeter grid on the screen.